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NAWCWPNS TP 8096

17th Annual Electronics Manufacturing Seminar Proceedings

Sponsored by
Electronics Production Technology Branch
Engineering Department

2-4 FEBRUARY 1993

DECEMBER 1992

NAVAL AIR WARFARE CENTER WEAPONS DIVISION
CHINA LAKE, CA 93555-6001

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NAVAL AIR WARFARE CENTER

DEPARTMENT OF THE NAVY
UNITED STATES OF AMERICA

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13. ABSTRACT *(Maximum 200 words)*

Presented are the proceedings of the 17th Annual Electronics Manufacturing Seminar, held on 2-4 February 1993, in Ridgecrest, Calif. The proceedings include the papers presented at the Seminar and cover all aspects of soldering technology and electronics manufacturing. The proceedings are a compilation of information provided by both nongovernment and government sources. The proceedings are published in the interest of furthering communication and broadening awarcness of current activities among soldering technology and electronics manufacturing specialists.

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Antimony removal
Chemical cleaners
Cleaning agents
Component solderability testing
Contamination testing
Information retrieval
Self-cleaning soldering
Shock-excited vibrations
Solder joint reliability
Solder paste flux
Solderability
Solderability inspection
Solderability problem analysis
Soldering attachments
Soldering stencils
Spin tinning
Surface-mount assemblies

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INTRODUCTION

The ever-changing, fast-paced technological advances being made today in electronics manufacturing present a challenge to us all. To help meet this challenge, we must work together. This Seminar—the 17th Annual Electronics Manufacturing Seminar—gives us an excellent opportunity to do just that. This Seminar promotes an open exchange of information on all issues of electronics manufacturing. It provides a forum for all persons involved in this technology, whether from government, industry, or academia. Here we can openly discuss these issues and share our ideas. Here we can work together toward our common goal: to improve the U.S. electronics industrial base. This year we are emphasizing environment protection through the elimination of ozone depleting chemicals or using other alternate technologies.

To help make this improvement we must continue to work toward the goals of productivity, producibility, and quality. We must maintain a concerted effort to resolve production-line problems. Then, we must develop process controls and methods to solve them. Because productivity, producibility, and quality are inseparable, it is critical that our designers learn from past problems and that they design for ease of manufacturing. The Navy is continuing to work with industry through the efforts of the Naval Air Warfare Center Weapons Division at China Lake and the Aircraft Division at Indianapolis.

The continuing goal of the Electronics Production Technology Branch at China Lake is to ensure producibility and quality in electronics manufacturing. We continually evaluate requirements and provide solutions for concerns specific to Naval Air Warfare Center programs, as well as for government and industry in general. We are continuing to support standardization of specifications requirements, as evidenced through the evolution of requirements from WS-6536E, DOD-STD-2000, MIL-STD-2000 Revision A and B, to MIL-STD-2000, and in providing guidance to industry in developing national standards ANSI/J-STD-001, ANSI/J-STD-002, and ANSI/J-STD-003. Developing technologies, processes, and manufacturing philosophies are providing unique challenges to us all. We are determined to remain in the forefront of this fast-paced world.

We are indeed looking forward to working with you to improve our electronics industrial base. We appreciate your interest in electronics manufacturing and thank you for joining us at this Seminar.

Dr. John W. Fischer, Head
Electronics Production Technology Branch
Product Assurance Division
Engineering Department

MANAGING THE TRANSITION ON A GLOBAL SCALE -- CHANGING THE CLEANING AGENT MEANS CHANGES TO EQUIPMENT, PROCESSES, PROCESS CONTROL SPECIFICATIONS AND STANDARDS

by

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I. INTRODUCTION

The production of electronics began with hand soldering, followed by manual cleaning, which reached its peak during the NASA program. Each step in the process tended to be considered on a stand alone basis, without thought being given to the preceding and following steps. Since each step had its own set of specifications, this led to a "patchwork" approach to overall quality. Recognized as a serious problem in the late '70s, when excessive solder defect rates were traced to a mis-match in printed wiring board solderability and permissible flux strength requirements, industry and DoD personnel started work on a unified soldering requirement. The crash drive to remove ozone layer depleting substances from electronics accelerated the trend to fully integrated process and material requirements and documents.

II. OVERVIEW

Several separate but related efforts were *running in parallel throughout the* late '70s into the '90s. The first track consisted of proper alignment of the solderability and soldering materials requirements for both boards and components to ease the assembly process. The second, driven by surface mount technology, centered on using more aggressive cleaning processes. In this case the process could include a more aggressive solvent, a more aggressive process (ultrasonics) or a combination of both. The third track consists of the CFC and Alternatives Benchmark, Phase 2 and Phase 3 programs, carried out by an industry (IPC), environmental (EPA) and military (DoD) cooperative team.

III. CHANGES

Track 1: Solderability and Soldering Materials

Printed Wiring Board Fabrication: The "October Project", a team of fabricators, assemblers and suppliers drawn from the IPC membership, has an ambitious charter to minimize waste, reduce costs and enhance competitiveness of team members. Waste minimization will be driven by use of additive processes and very tight dimensional stability requirements of the incoming laminate and outgoing product. Topology control will help the assembler meet Six Sigma requirements during the placement and subsequent assembly processes. New technologies are needed to generate processes with the robustness needed to achieve high yields with minimal environmental impact. These advances will take place in PWB fabrication, with the fabricator applying the solder to the PWB in a controlled manner, tailoring the pads for minimal defects in the placement, reflow and optionally, cleaning, operations, which will comprise the assembly process floor of the future. The processes the PWB fabricator will be using to facilitate UFP are described below. The first involves electroplating, with its environmental concerns, while the others provide "Photo-Defined Solder Deposits (PDSD's) (Freidrich, Weinhold, Maiwald). These latter technologies have been incorporated in the new IEC TC91 (Surface Mount) Assembly Process documents (Solberg).

Plated Solder Bumps: Since plating with solder is a well-known technique used in the PWB industry, some companies are using this technology to apply "solder bumps" with a thickness of 100 um or more. This technology produces a flat land pattern ideal for surface mounting, but requires the use of a second dry film resist, with a thickness in excess of 60 um, to prevent overplating. Since the time spent in the Sn/Pb plating baths to obtain the solder bumps can be as long as 90 minutes, and since two layers of dry film resist must be processed and stripped, manufacturing times are longer, chemicals consumption is higher, resulting in higher PWB manufacturing costs.

These plated deposits do not melt at the same eutectic point as Sn/Pb, so a reflow solder process is needed. However, this would destroy the flat surface profile of the surface mount land pattern solder pad. This means that the solderability of plated solder deposits is not as good as that of reflowed Sn/Pb. Thus a more highly activated flux is required during component soldering which then requires a more intensive assembly cleaning process. The additional fabrication costs for the plated solder bump are relatively high, but these additional costs can be offset by reduced assembly costs, since the process of stencil printing solder paste onto the board is eliminated. Where only a few assemblies are involved, costs can even be reduced, since there are no stencil set-up costs and the inconvenience of having stencils in the assembly area plus a cleaner for them is avoided.

In some cases, plated solder bumps are the only possible solution for applying a well-defined amount of solder onto fine-pitch surface mount PWBs, provided that Sn/Pb plating will be suitable, since not all solder alloys can be electroplated in this fashion.

OPTIPAD*: A temporary polymer mold is used to define the SMD land pattern area. Molten solder is then deposited on the land pattern to form the solder deposit.

Process description: After the finished PWB panel is solder masked and HASL'd, but before profiling, a temporary solder mask is applied to the manufacturing panel and then processed in the usual manner to provide a polymer "mold" for the SMD lands. After the temporary solder mask has been cured, molten solder is applied to the total panel using patented OPTIPAD solder coating equipment. This equipment forces the solder under pressure into the polymer molds of the SMD land pattern. A membrane then seals the molten solder in the mold until it has cooled and the solder is "frozen" into a solid metal deposit with a flat surface. Next, the temporary solder mask is stripped off. The manufacturing panels are then profiled to either assembly panel or final board size, are cleaned, dried, tested and shipped to the assembler.

In this process, the thickness of the solder deposit is determined by the thickness of the temporary solder mask which is used. Since this mask is a photo-definable polymer, the resolution and line definition is pre-determined by the photo-polymer which is used. With a 125 um (5 mil) thick solder mask, it is possible to manufacture pitch sizes of 300 um (12 mils). Although the solder coating equipment is not yet available on the market, prototype boards can be manufactured to demonstrate the capability of the process for mass production as well as for faster manufacturing through-put at the PCB assembler. Micrographs of lands on a PWB which have been manufactured using this process clearly show that the thickness of the lands are greater than the solder mask which surrounds the pads. In general, the thickness of the solder is between 120 and 130 um (about 5 mils). This technology has been designed to provide a solid, even metal deposit on the SMD land pattern. The composition of the deposited metal alloy depends on the type of solder which is used in the OPTIPAD solder coating machine, and can be changed according to the requirements of the user. Since the stencil printing of solder paste is no longer necessary, the process speeds up and simplifies the soldering process in the assembly area. Also, it is not dependent on being able to electroplate the desired soldering alloy.

SIPAD: The third process which will enable the PWB fabricator to supply to the assembler circuits with a solid, flat solder deposit is the SIPAD process developed and patented by Siemens AG, in Germany.

Process description: The SIPAD process is used on the finished printed circuit board after solder masking. The solder mask used in this application should have a thickness of 100 um, this thickness being important since it is this which determines the amount of solder applied to the surface of the circuit.

The surface of the printed circuit board is first of all activated, after which the solder paste is stencil printed onto the SMD solder land areas. It is necessary to use a stencil to ensure that the deep well formed by the solder mask is filled with the right amount of solder paste. An activated solder paste can be used which may give a more homogeneous solder deposit after reflow. After the solder paste has been re-flowed, the meniscus of the molten solder is flattened using a hot metal plate. The metal plate is cooled down to a temperature below the melting point of the solder, so that the solder freezes inside the solder mask well. The pressure imposed by the metal plate produces a flat surface which is virtually level with the surface of the solder mask. The surface is cleaned after the panel has reached room temperature. Since no components are attached to the surface, cleaning can be undertaken very effectively in standard cleaning equipment used in the PWB fabrication or assembly processes. The viability of this technology has been demonstrated for circuits with a centre-to-centre pad distance of down to 400 um. However, as stencil printing and solder pastes are used in this process, the limitations inherent in stencil printing technology need to be taken into consideration. On the other hand, since the application of the solder paste is undertaken in the PWB production environment, on a highly activated copper surface, solder wetting of the land pattern for the fine-pitch components can be achieved more easily than if the lands are wetted after the PWBs have been shipped, stored and even baked before the application of the solder paste. The solder paste, which has been forced by this process into a clearly defined three-dimensional well, will have longer guaranteed storage times than if the HASL process had been used.

Printed wiring boards must have much tighter dimensional tolerances to minimize the compensation that is generally built into the remainder of the process equipment, as proposed by the October Project members. While the use of additive plating will minimize waste in fabrication, the process is slower and will require the development of an aqueous processable resist that can withstand the exposure to the harsh additive chemistry and conditions. Surface Insulation Resistance (SIR) 3-4 decades above the values presently available could be easily obtained by simply implementing the commercially available SA fusing fluid/HCS semi-aqueous cleaning technology developed in the mid-'80's (Zachariah, Kenyon) for PWB's requiring a fused tin/lead electroplated surface. Development stage HASL fluids based on the SA technology also provide dramatic improvements in SIR values, compared to current processes. Both processes need to be phased in as rapidly as possible to enhance PWB electrical parameters and overall quality. Meanwhile, processes are becoming available that provide flat pads (Plated Solder Bumps, OPTIPAD*, SIPAD) and solder mask to maximize alignment in placement, provide the controlled volume of solder needed for joint formation and eliminate solder balls. The joining can be accomplished with either the special SA flux described above, followed by semi-aqueous cleaning; or by the use of a fugitive flux whose residues vanish during the reflow process, thus not requiring any cleaning. These technologies should work well on bare copper PWB's currently favored by certain users for cost and environmental reasons, although some of the less forgiving formulations may require an inert atmosphere for minimum solder defects.

The first comprehensive computer controlled electronic assembly process was demonstrated by Westinghouse (Davy), who showed that it was possible to automate the entire fluxing, soldering and cleaning process to maximize yields while reducing the impact of chemical usage. Flux was applied by an airless spray system, which both tailored the amount of flux needed while using fresh flux each time eliminated the typical contamination and changes that occurred in fluxers. Minimal flux meant that the preheaters could be eliminated, reducing energy costs and indirectly, production of greenhouse gases. Automatic adjustment of the conveyor speed according to bar codes on the PWB ensured correct soldering parameters for each part number. The cleaning operation was similarly automated and optimized to ensure minimum chemical usage. While developed to automate the process, this work was the seed for all the environmentally responsive process work that followed.

The advent of Surface Mount brought about step changes in wave soldering, as well as introducing the concept of reflow soldering. To understand the changes in wave soldering, we first have to examine reflow soldering, particularly the use of solder paste. For the first time we saw precise control of the amounts of materials needed to accomplish mass soldering. Exactly the right amount of joining metal (solder) and fluxing formulation were applied to the point where the metallurgical and electrical junction (solder joint) was required. Components were added by high speed automated equipment, followed by mass reflow by contact with a hot gas (air, nitrogen, fluorocarbon) and/or infrared emitting panels or lamps. Cleaning within 15 minutes of reflow was preferred to completely remove all flux residues and solder balls prior to changes in the residue that tended to make it significantly difficult to remove (Lermond). The concept of materials conservation/minimization was extended to the wave solder step that typically followed reflow, in combination with either a turbulent "chip" wave followed by a smooth wave or a single smooth wave containing a variable power oscillating plate to produce micro ripples in the wave surface (Electrovert, Omega wave). Both concepts were aimed at providing pathways for any residual flux volatiles to escape quickly without blocking solder contact with the pad and component terminations that needed to be joined. Preheating was controlled and optimized to prevent chip cracking during wave and reflow soldering, plus eliminating the "drawbridging" or "tombstoning" defects seen with early surface mount processes (Prasad). A new family of fluxes with minimal non-volatile residue appeared in the mid '80s, based on the earlier work of Rubin and the German DIN FSW-32 classification. Typically consisting of 2-4% solids, with 75-80% of the solids being dibasic organic acid activators, they became known as AT or "Activated Thinner" fluxes (Bernier). Designed to have almost quantitative consumption of the solids (activators) during the soldering process, the need for cleaning was generally eliminated. Cleaning was still found necessary in the case of RF circuits or if excessive solder balling was present. Realization of the full potential of these materials did not occur until the development of the ultrasonic spray fluxer by an AT&T team (Guth). Guth's team realized that the high loadings of additives required to promote foaming resulted in unacceptable residue levels and degraded the surface insulation resistance. The new fluxer permits precise control of the flux application process, resulting in SIR levels that are both predictable and in compliance with the exacting Bellcore requirements (Balmer, Culver).

The most recent step in chemical waste elimination and defect reduction took place with the introduction of controlled atmosphere soldering in Germany (Seho). This process used a nitrogen blanket doped with ca. 600 ppm of formic acid as an oxygen "getter" in the soldering machine to allow traditional flux to be eliminated, however a 10% solution of adipic acid in 2-propanol was often substituted to ensure complete oxide removal. Next generation equipment was soon able to maintain the nitrogen blanket oxygen level at < 10 ppm, which eliminated the need for formic acid. Some users are now eliminating the adipic acid in favor of highly controlled application of AT flux. Faced with ever accelerating CFC-113 and 1,1,1-trichloroethane (methyl chloroform) phase-out schedules, industry realized that the days of standard, off the shelf cleaning processes were over. For the first time, many did a thoughtful assessment on the need for cleaning for their product, its end-use environment and the consequences of failure. Many found that instituting a highly controlled low solids (AT) flux plus solderability testing would permit the elimination of the cleaning step with only minimal risk. Process control is crucial for

success, some users reported the need to titrate the AT flux for acid content every 15 min. for complex and critical circuits prior to the implementation of the ultrasonic spray fluxers (Klugman).

Pastes: The genesis of defect free ultra-fine pitch soldering and cleaning occurred in the mid '80's at Westinghouse where first 500 um and later 400 um pitch high lead count VHSIC devices were attached and mass vapor phase soldered without the use of solder paste, adhesives or fixturing. Instead, heavily plated solder pads were coated with a special synthetic activated (SA) flux, the components were placed with a vision placement system, followed by soldering using a computer controlled, heat seeking elevator vapor phase system. The resulting assemblies, which were solder ball free, were easily cleaned in a mild CFC solvent (Keen, Kenyon). While this process produced the most reliable solder joints seen in the VHSIC program (DeVore, Wild), the use of a non-MIL-F-14256 compliant flux prevented its adoption, even when Martin Marietta demonstrated that the same success could not be accomplished with rosin flux that complied with the specification (Love). The Westinghouse work, which also demonstrated the concept of dry film solder mask "frames" around the solder pads to eliminate bridging, lay dormant for many years, as the industry worked from 2500 um pitch to 1250 um to 800 um to 625 um and presently to 500 um and below.

The technology roadmaps developed by many industry leaders are aimed at using 250 um pitch devices in production within three years. Meeting this goal by further modification of traditional solder paste flux formulations to achieve the required printing will probably have a negative impact on the drive to lower post-reflow residue levels. Also, current powder production methods are straining to meet the yields of Type 3 powder needed, thus Types 4-6 will be limited in quantity and pastes made with them will command prices of 3-4 times the present levels. Stencils must be thinner and will be more fragile, especially if the trend to stainless steel squeegee blades continues.

Solder paste today is classified according to the activity of the flux portion, before and after reflow (ANSI/J-STD 004-006) and by the post-reflow residue level as determined by TGA (Beikmohamadi). While all users would like to use a L0 (no halide, non corrosive) Class D (<20% residue), air reflowable solder paste, this is not always possible unless the PWB's and components have been properly manufactured and stored. Solder paste for ultra fine pitch will require new processes to make oxide free powder in high yield in the extremely fine Classes 4-6. In tandem with powder development, solder paste manufacturing processes that provide exactly the same material from lot to lot must be implemented. No Clean extremely low residue formulations that provide sufficient activation to cope with reflow of solder onto bare copper PWB's in air without solder balling will be favored, allowing users to standardize processes world-wide with less concern over costs.

Specifications: Soldering materials specifications, formerly distributed among various military, industry, company, national and international documents have been harmonized into a set of three documents for use world wide, using the U.S. Federal Specification QQ-S-571 as a "shell." (Kenyon, Russell). The three documents, ANSI/J-STD-004, ANSI/J-STD-005 and ANSI/J-STD-006, cover Soldering Fluxes, Solder Pastes and Solder Alloys and Forms, respectively. Incorporating the best thinking from experts world wide, the documents are being formatted for submission to ISO for international acceptance.

Track 2: Cleaning Processes

Cleaning Agents: Initially the advent of SMT drove users from aqueous processes to solvent cleaning, based on the superior Wetting Indices (Kenyon) of the various solvents. However the post reflow paste residues proved more difficult to remove than wave solder residues. Suppliers and users alike attempted to increase the solvency power of their solvent formulations, only to find compatibility problems with materials of construction and marking inks. After some initial problems with attack on the laminate caused by long term exposure to boiling methyl chloroform (solved by implementing tetrafunctional resin systems), it became recognized that boiling ultrasonics combined with a mild solvent offered a preferred route to the desired level of cleanliness.

Ultrasonics: Although well known for its ability to augment the mild solvents preferred for compatibility reasons, early component packages, especially the TO-5 family of metal cased packages, tended to transmit ultrasonic energy to the actual gold or aluminum wires that connected the die to the lead frame. Some evidence was gathered (Martin-Marietta) that showed that ultrasonic cleaning could cause damage to components of the late '60s designs, although it was not clear if this was the more powerful 20-25 kHz units normally used in aqueous cleaning applications, or the gentler 40 kHz that became the standard for use with solvents for electronics cleaning until the advent of today's variable frequency (sweeping) ultrasonics. Once these early metal or metal cased packages were supplanted by the plastic packages, which tended to absorb and attenuate the ultrasonic energy transmitted to the die bond wires, the commercial world embraced ultrasonics as a path to better cleaning in a shorter cycle time. Even the medical world found that ultrasonics provided two advantages over conventional solvent immersion or spray cleaning. First, pacemaker design required "piggy backed" integrated circuits to get the needed packaging density, which created a problem with very small stand-offs between the components mounted in this fashion. Second, "infant mortality" of the components required rework and re-testing, which extended delivery schedules. Ultrasonic cleaning solved both problems by cleaning the tightly packed components while transmitting sufficient energy to weed out the components that would have failed during the "burn in" cycle (Stach and Alexonis, NEPCON East). The "show stopper" to general adoption of ultrasonics was the prohibition found in many military documents. With the advent of surface mount technology, introduced in the U.S. with LCCCs for the military, there was a resurgence of interest in ultrasonics to clean under these packages, once it was clearly shown by the glass slide studies of Hale & Steinacker comparing time to achieve visual cleanliness vs spacing that ultrasonics was the only viable cleaning method that maintained productivity. After reviewing the data, the U.S. Navy EMPF laboratory at China Lake drew up a 3 year test program to re-assess the viability of DoD use of ultrasonics for cleaning the new surface mount designs coming into production using the CFC solvents found in the relevant Mil Specs plus some aqueous materials. Meanwhile, a UK government funded ultrasonic cleaning study commenced at GEC's Hirst Reseach Centre, which included some of the newer cleaning agents, such as the hydrocarbon/surfactant (HCS or Semi-Aqueous) materials being qualified under the EPA/DoD/IPC-Industry Phase 2 program. Presented at the EMPF Soldering Seminar ('MM), the GEC studies showed that ultrasonics was a viable method for cleaning today's surface mount packages, especially with the new non-ozone depleting cleaning agents. The EMPF and GEC teams joined forces to develop a Component Screening & Qualification Protocol, which will be administered through the IPC Ultrasonic Cleaning Task Group. The Task Group will also maintain a list of components that have been tested and qualified. The latest version of the mil specs now allow the use of ultrasonics for cleaning of printed wiring assemblies, provided the contractor has carried out the required screening tests on the components.

Track 3: Alternative Cleaning Agents & Processes

To address the need for a Montreal Protocol driven environmentally preferred material that would "drop into" existing cleaning equipment, a chlorocarbon diluted version of the nitromethane stabilized CFC-113/methanol azeotrope accepted as the industry standard was described in a Tech Brief at the EMPF/NWC Seminar in 1988 (Kenyon). EPA leadership present at the program, recognizing the potential for reduced ozone depletion if such materials were adopted, were surprised to learn that the military specs precluded implementation, however this could be overcome by a test program that demonstrated that the new materials cleaned as well or better than the CFCs currently in use (Andersen, Kenyon). The following morning a core group from EPA, DoD and Industry met to set up the basis of such a test program (Andersen, Kenyon, Steinacker, Johnson, Peacock). This program grew into the CFC Benchmark Ad Hoc Solvents Working Group. The team generated a test board/assembly, wrote a test plan, ran two duplicate sets of tests at two Navy facilities and presented the results at a major IPC meeting, requiring only 14 months to accomplish the entire task. Once the Benchmark for the present standard cleaning agent was set, Phase 2 -- testing of candidate new cleaning materials against this benchmark could commence. This effort, monitored by a TMVT or Test Monitoring and Validation Team, ensures that an oversight group is present for each test, in addition to reviewing the test plan before the test date is set and then reviews the data when the test is complete. The TMVT must decide, based on the data, if the candidate material is better than/equivalent to/not as good as the benchmark solvent. All results are published and available from the material sponsor upon request. Phase 3 of the program allows changes to other parts of the test protocol. Sub-sets of Phase 3 include studies of Water Soluble Fluxes/Pastes, No Clean Fluxes/Pastes and Controlled Atmosphere Soldering. (Turbini, Hymes, Lichtenberg)

While many users converted to "no clean" processes (which often required increased vigilance and testing for solderability) many more found that they could not eliminate the "safety net" provided by a cleaning step in their production line. The choice of cleaning agent for the future fragmented into four general families of materials:

Saponification: an established process for rosin flux removal by chemical conversion of the residue; the conversion process is the rate limiting step in the process, large volumes of aqueous waste to drain.

Aqueous: tap or deionized water, used for water soluble flux removal, large volumes of aqueous waste to drain, concern over heavy metals in effluent.

Semi-aqueous: (also called Hydrocarbon Surfactant, UNEP), a new technology characterized by a hydrocarbon wash step, followed by a water rinse, decanting of the resulting emulsion after it breaks to allow recycle of the hydrocarbon and water. In a recent development, the water is further purified by passage through a membrane cartridge prior to recycle to rinse, thus minimizing the volume going to drain. Semi-aqueous processes can be used to remove rosin, synthetic activated (SA), water soluble and certain low solids (AT) fluxes; thus have become very popular with contract assemblers or users reluctant to change their flux/solder, paste/reflow processes.

Flammable: this class includes volatile materials, such as alcohols, with (Baxter) or without the use of a fluorocarbon inerting vapor blanket, Stoddard solvent, mineral spirits, etc. Alcohol is used successfully in certain in-line applications in Germany, however it has been used traditionally in pan and brush cleaning for small runs or prototype cleaning.

Cleaning Equipment & Waste Management

The change in cleaning materials meant that a change is equipment was mandated. Many users had little experience with water-based processes, since so many of the mil specs were built around solvent cleaning. Thus the membrane systems that allowed users to recycle the rinse waste and "close loop" semi-aqueous systems were quickly accepted, since no water disposal permits were needed. Waste streams containing soluble organics and heavy metals require more elaborate treatment for compliance with existing or future regulations.

Specs & Stds.

The first target for change was the body of Military Specifications that had embodied the use of CFC-113 and MCF over the years. Many of these specs involved the use of these solvents as test solvents to determine the resistance of the various marking inks, solder masks, wire insulation, adhesives, plastics, elastomers and encapsulants used to produce high rel assemblies.

MIL-STD-202, Method 215 and the corresponding method in MIL-STD-883.

MIL-F-14256, the classic liquid rosin flux spec., was first incorporated in the ANSI/J-004, then modified to permit the use of two classes of water soluble fluxes, those with polyglycols and those without.

MIL-STD-2000 & MIL-STD-2000A replaced most of the mil soldering documents. While these specs do allow the use of non-rosin fluxes, they must be part on an integrated flux, solder, clean and test protocol.

Test Methods

Initially, all the test methods used for cleanliness assessment were based on a solvent cleaned rosin flux residue. The integrated test methods required above are just now being developed through the IPC Cleanliness Assessment Sub-Committee (Johnson, Sellers). Eventually there will be an appropriate ionic conductivity, surface insulation resistance, electrochemical migration resistance and residual organics method for each flux/solder/deflux process.

Hand Soldering & Cleaning: Traditionally, the hand soldering process was followed by either a simple cleaning in a batch vapor defluxer or by a localized solvent application combined with brushing. The former was preferred, since the latter merely accomplished the spreading of the residues over a larger area but did not remove them from the surface of the assembly. Recent thinking, driven by the equipment shortfall and lack of equipment as simple and inexpensive as the two-sump vapor defluxer, has given rise to a new concept for post-hand solder cleaning, which is applicable to touch-up, re-work and repair operations. In this process, the contaminated area is wetted with a high viscosity liquid cleaner, so it stays in place during the time required to dissolve the residues from the surface of the board. When all the residues are in solution, the cleaner is removed via vacuum through a water scrubber, so only water vapor is discharged. The cleaned area may be rinsed with 2-propanol to remove any traces of the cleaner and quickly dry the surface of the assembly to prepare it for a subsequent conformal coating step.

IV. CHANGE ON A GLOBAL SCALE

The changes cited above have been carried forward on a global basis; first with the contributions of the GEC personnel ultrasonic studies, the UK and Nordic Community versions of the Benchmark program, and the cooperative work on the soldering materials documents. Since the vast majority of the countries have signed the Montreal Protocol, global companies are standardizing processes world wide in compliance with the new cleaning processes.

Bill Kenyon, Senior Scientist, DuPont Electronics, has been involved in product, process, and test development for the past 18 years. He has focused on cleaning-process studies, flux/solder/deflux evaluations, and has pioneered the work responsible for modern synthetic activated (SA) flux technology. He co-founded the CFC Benchmark & Alternatives Ad Hoc Task Group and pressed for an industry semi-aqueous alternative cleaning process offering.

These contributions have led to his being awarded the 1990 Stratospheric Ozone Protection and Marketing Excellence Awards by the EPA and DuPont, respectively, who also nominated him to serve on the United Nations Environmental Program (UNEP) Technical Assessment Panel.

Bill is active in trade, professional, and industry association leadership activities, and chairs or is a member of several national and international committees.

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Manufacture of Aluminum Custom Hybrid Microwave Packages

M. D. Grgas and G. G. Pinneo

TRW Manufacturing Division

Redondo Beach, CA

Abstract

Five aluminum-based materials were explored for fabrication of custom microwave hybrid packages for spacecraft electronics applications. Machining, plating, matched-glass feedthrough installation, substrate attach and laser lid-weld assembly operations were addressed. Test packages passed MIL-STD-883, Test Method 2009.8, Class-K, thermal-shock and thermal-cycle stress-tests from -65°C to + 150°C with no change in He leak-rate; packages remained in the less than 1 x 10^{-9} atm-cc/ sec He range.

Key words: Custom hybrid microwave packages, hermetic modules, 6061 aluminum, A-40 aluminum/silicon alloy, A-390 high-silicon aluminum alloy, Al/SiC metal matrix composite materials, (4 volume-% ranges detailed) matched-glass feedthroughs, gold/tin eutectic solder, low-labor feedthrough installation, removal and replacement of FT's, polycrystalline diamond machining, casting to near-net shape

Introduction

This aluminum-based package work was undertaken to provide dramatically improved thermal transfer, lighter weight and controlled C_{TE} custom microwave hybrid packages for spacecraft/avionics electronics using GaAs IC's. The primary aerospace electronics package material has typically been one of the nickel-iron materials. Kovar[R], for instance, is often used to allow direct-glassing of matched-glass feedthroughs (FT's). Some designers use Alloy 46 with brazed-in FT's. While both Kovar[R] and Alloy 46 have excellent C_{TE} properties, neither have acceptable thermal transfer properties for use in direct contact with GaAs chips, nor are they light-weight materials.

Custom Hybrid Package Materials

We examined and processed 6 types of aluminum-based materials:

- "Plain" 6061 T6 aluminum served as a baseline material
- Sumitomo's proprietary A-40 high-silicon hypereutectic sintered metal alloy
- Reynold's A-390 casting alloy
- DWA's bulk-reinforced 6061 Al/SiC metal matrix composite materials (MMC) (both 40 vol-%SiC and 55 vol-% SiC, extruded and forged)
- British Petroleum Research's squeeze-cast, selectively-reinforced 6063 Al/ 59 vol-% SiC MMC material, a near-net shape approach
- Alcoa Innometalx's 65 vol-% Al/SiC, 10% Si, vacuum-assisted high-pressure diecast MMC, another near-net shape approach

Approach

We initially designed and fabricated a test-vehicle we called the "Model Package". Figure #1 shows an array of 6061 Model Packages after initial thermal shock and cycling. We made Model Packages in 6061, A-40 and started to make them in A-390. Figure #2 shows a plated 6061 Model Package in the copper solder fixture, an A-390 rough-machined Model Package blank to the left and a finish-machined, unplated A-40 Model Package to the right.

The A-390 material we were presented with was found to be too porous to be even marginally acceptable and was dropped. Figure #3 shows a "close-enough" view of a typical A-390 rough-machined blank to determine extensive porosity. Several casting houses would like to cast A-390 to near-net shape and insist that porosity isn't an issue. If fully dense A-390 material becomes available, it may be able to be utilized as a package material.

As a result of time constraints, we adopted a package that had been designed and had a mold made for squeeze-casting by British Petroleum Research, Warrensville OH. BP's Transmitter/Receiver Package (T/R Module) is smaller than our "Model Package" but is adequate to allow FT emplacement, substrate attach, lid-weld and preliminary thermal shock and thermal cycling to conducted. Figure #4 shows the as-received selectively-reinforced BP T/R module and a selectively-reinforced cover made by machining away the side-walls from one of the cast modules. Figure #5 shows a T/R module with FT's Au/Sn soldered into each end, a pair of matched-glass FT's and a T/R module in a copper solder installation fixture ready for solder reflow.

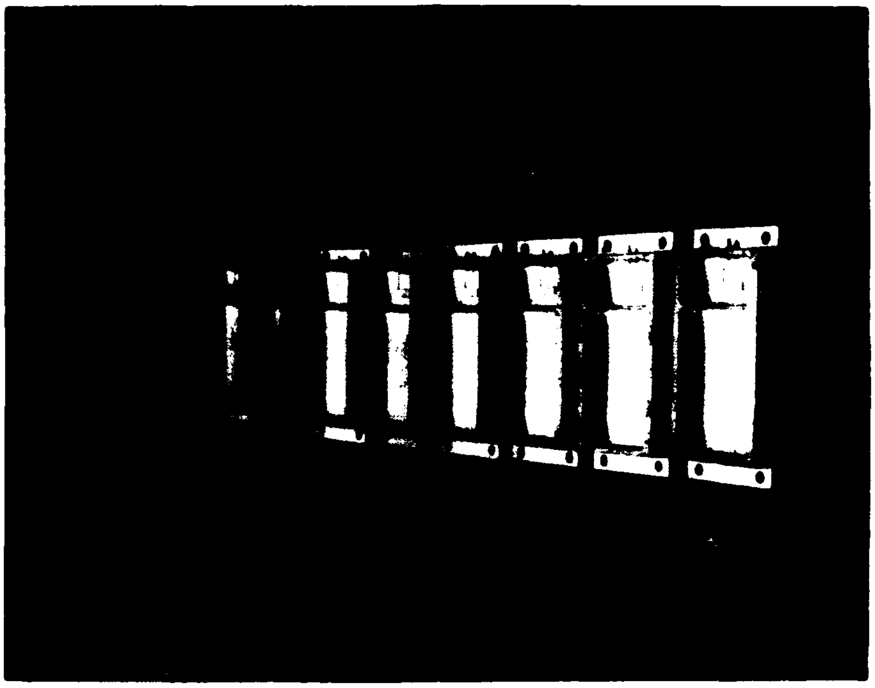

FIGURE 1. 6061 Al Model Packages After Au/Sn Installation of FTs and Thermal Stress Testing.

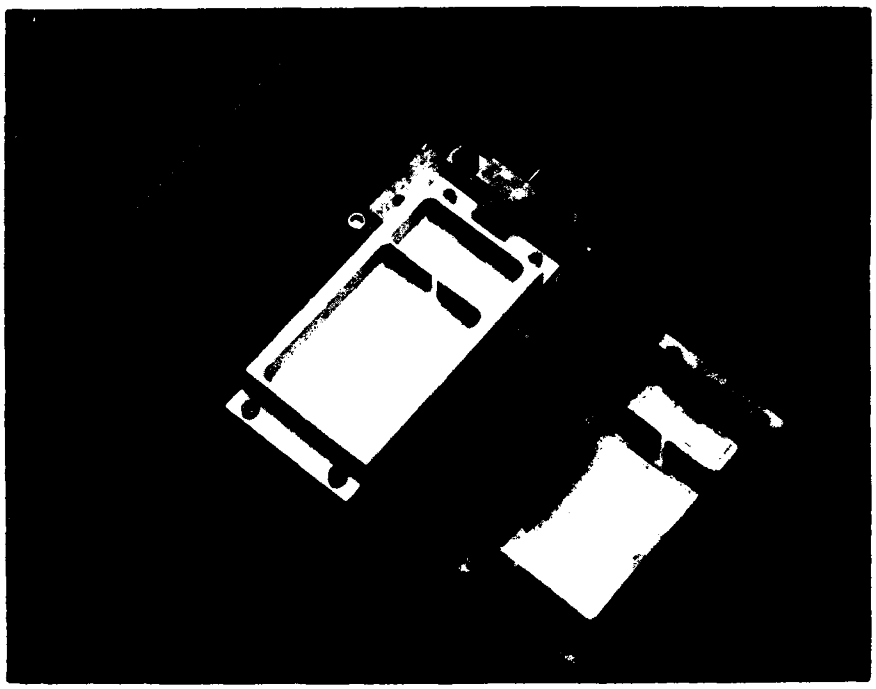

FIGURE 2. 6061 Al Model Package in Copper Solder Fixture (Center); Sumitomo A-40 Unplated Model Package (Right); and Rough-Machined, Porous A-390 Model Package (Left).

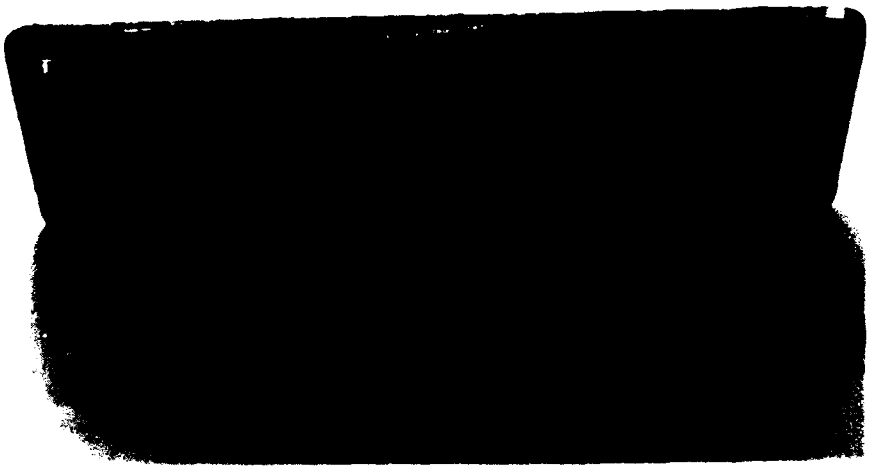

FIGURE 3. Reynolds A-390 Rough-Machined Model Package Shows Porosity.

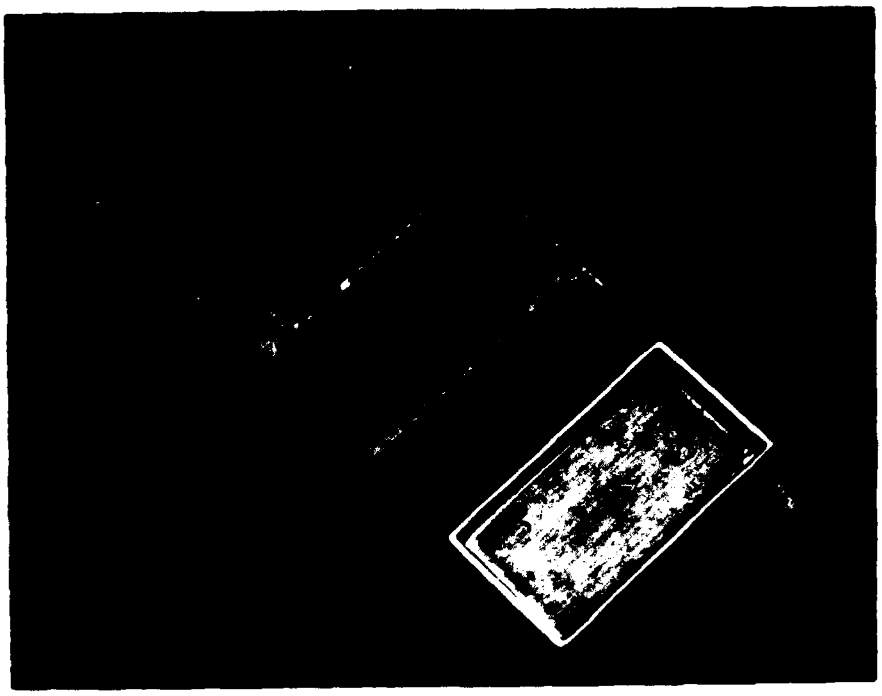

FIGURE 4. BP Squeeze-Cast Al/SiC T/R Module, Selectively Reinforced 59 Vol-% Al/SiC. Unreinforced plug in center for future feedthrough emplacement.

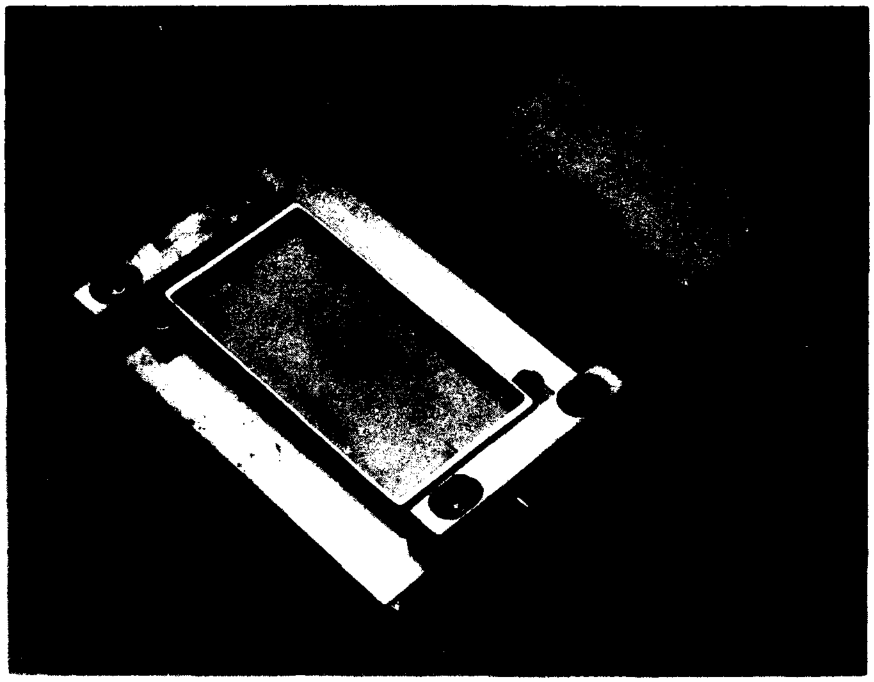

FIGURE 5. BP T/R Module With FTs Installed, FTs, and Second T/R Module Tooled-Up for Solder Reflow.

FIGURE 6. First In-House Polycrystalline Diamond-Machined, 40 Vol-% Al/SiC Box Package With Au/Sn-Installed FT.

FIGURE 7. 55 Vol-% Al/SiC Driver Modules PCD-Machined From Forge-Clad Bulk Material.

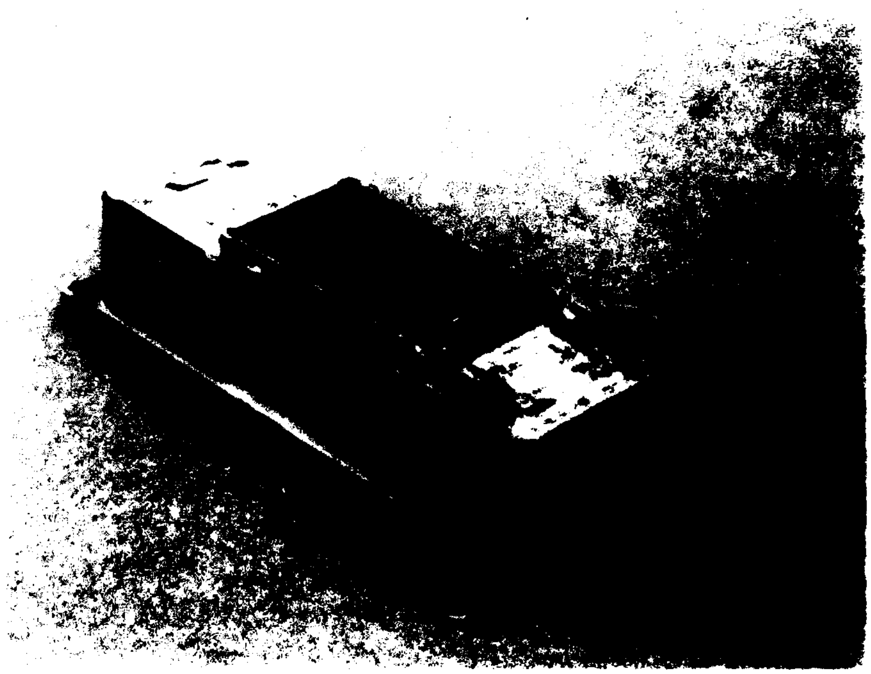

FIGURE 8. Alcoa Die-Cast 65 Vol-% Al/SiC Driver Module (Top View).

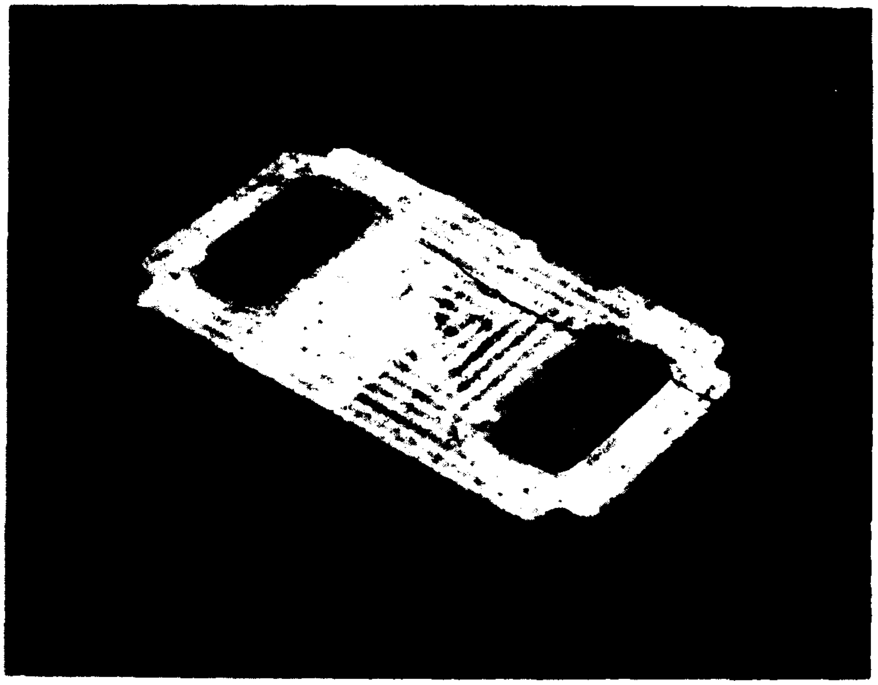

FIGURE 9. Alcoa Die-Cast 65 Vol-% Al/SiC Driver Module (Bottom View).

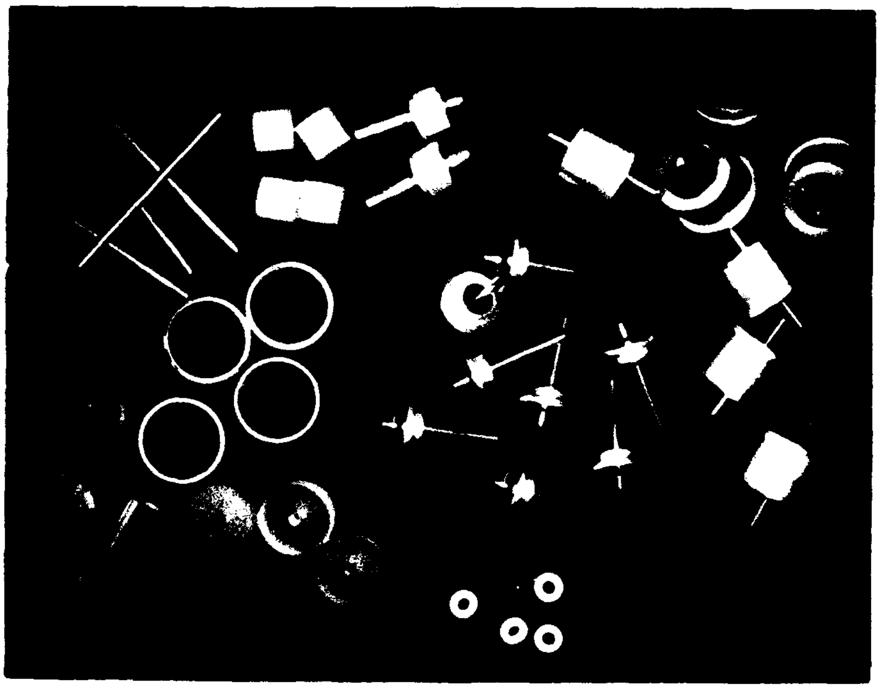

FIGURE 10. FT Components Including Kovar[R] Pins and Ferrules, Corning 7052 Glass Beads, Alumina Reinforcing Discs and Finished FTs.

Using polycrystalline diamond (PCD) endmills, another simple "box-package" was machined from DWA's bulk-reinforced Al/SiC MMC material. Figure #6 shows this simple package after installation of one FT. We purchased PCD endmills and drillbits from 3 vendors, todate: Precorp, Provo UT, Robb-Jack, Lincoln CA and Norton Co., North Attleboro MA. Tool design and construction varies widely from these vendors; but, performance of these tools has been generally quite acceptable for the very fine details of custom hybrid microwave packages.

We then made slight modifications to a third test article: a solid state amplifier Driver Module shown in Figure #7. This package was PCD-machined from DWA's bulk-reinforced, 55 vol-% Al/SiC material that had been forge-clad with 6061 Al to allow direct laser lid welding of 4047 Al lids.

Our final test article was this same Driver Module modified for "insert-casting" by Alcoa using a SiC preform or insert to result in 65 vol-% Al/SiC. This near-net shape part is shown, as-cast, in Figures #8 & 9.

Table #1 shows some selected physical properties of the 5 materials. The 4th column, coefficient of thermal expansion, C_{TE}, shows why we were interested in each material and what weighting we might give to each of the materials in selecting for a composite value in terms of best thermal transfer, light weight, controlled C_{TE}, cost, availability, machineability, and ready plateability.

Tables #2 and #3 show some of the machining results and milling parameters for the 6 materials. Our initial attempts to cut Al/SiC MMC materials with coated-carbide endmills rapidly produced badly eroded tools. Fortunately, much is being done with PCD and single-crystal diamond cutting tools today. We used both two-fluted, straight-flute PCD endmills and spiral-fluted polycrystalline diamond insert endmills quite successfully. We PCD-machined 3 packages made of 40 vol-% SiC/6061 Al and 12 SSA DM's to print specifications with no significant problems using PCD endmills and drillbits from 3 vendors. This PCD "tool-set" of some 20-odd tools is still functional after making the test-articles More remains to be learned about using these expensive new tools for package machining, but it is an understatement to say that they're "pretty interesting"!

Package Fabrication Procedure

The 6 package materials were obtained in bulk form, squeeze-cast form, and insert-diecast form and were then rough-machined, finished machined, deburred, zincated, electroless Ni-plated, Au-electro-plated and then matched-glass FT's were installed using an 18-minute fluxless 80Au/20Sn solder reflow cycle in one of two DAP 2200 thermal processors.

Matched-Glass Feedthroughs

TRW has an in-house feedthrough-glassing capability that has been reported in a paper presented at the 1990 Chicago ISHM Symposium. Work-in-progress now includes the fabrication of quasi-matched-glass FT's using Kovar ferrules and pins and Corning's #7070 glass beads. #7070 glass allows fabrication of somewhat smaller RF FT's than does Corning's #7052 glass. Details of this newer FT effort will published at a later date.

Using our standard glassing procedure, we designed and made 5 different configurations of matched-glass (Corning's #7052 glass) FT's to install in the 3 companion packages using a fluxless gold-tin (Au/Sn) solder reflow process. Figure #10 shows a macrophotograph view of some of the FT's used.

TABLE #1 - Packaging Materials, Selected Physical Properties

Material Name	Physical Description	Vendor Name	T_{CE}	Density	Thermal Conductivity
Kovar[R] (ASTM F-15 Alloy)	29%Ni/17%Co 54%Fe	Fagin -- Carpenter	5.1 X 10^{-6}/°C	8.36 g/cc	17.3 W/m K
Alloy 46 (ASTM F-30 Alloy)	46%Ni/54%Fe	various	7.4 X 10^{-6}/°C	8.+	
6061 Alum	wrought	various	23.6 µm/m K	2.70 g/cc	201 W/m K
6063 Alum	wrought	various	25.6 µm/m K	2.69 g/cc	167 W/m K
A-40 Alum	powdered metal (consolidated)	Sumitomo	13.5 X 10^{-6}/°C	2.53 g/cc	130 W/m K
A-390 Alum	casting alloy	Reynolds	18.5 X 10^{-6}/°C ?		--
Al/SiC	metal matrix 59 v-%/6063	BP Research DWA Composites	8.5 X 10^{-6}/°C	3.00 g/cc	200 W/m K
Cu/W	sintered Cu/W (powder metal)	Sumitomo 80/20 CMW 76	8.5 X 10^{-6}/°C 7.6 X 10^{-6}/°C	15.65 g/cc 15.56 g/cc	240 W/m K 180 W/m K
Beryllium	E-60 grade (metal)	Brush Wellman	6.1 X 10^{-6}/°C	2.52 g/cc	240 W/m K
Molybdenum, metal		various	5.1 X 10^{-6}/°C	10.22 g/cc	132 W/m K
Alumina	Al_2O_3 (substrate)	various	6.7 X 10^{-6}/°C	3.6 g/cc	12.0 W/m K ?
Beryllia	BeO (substrate)	various	7.6 X 10^{-6}/°C	2.69 g/cc	170 W/m K
Aluminum Nitride	AlN (substrate)	various	4.7 X 10^{-6}/°C	3.24 g/cc	170 W/m K
Gallium Arsenide	GaAs active devices	various (TRW)	6.5 X 10^{-6}/°C	5.3 g/cc	54 W/m K
Silicon	Si	various	4.2 X 10^{-6}/°C	2.3 g/cc	151 W/m K

TABLE #2: Summary of Machining Results

Material Tested	Cutting Tooling Material	Coolant	Machineability	Cutting Tool Wear	Surface Finish	Able to EDM	Tap Material	Tap Lubricant	Thread Quality	Tap Wear	Comments
6061-T6	Carbide	Flood, H_2O-soluble oi	Excellent (Conventional and climb-cut)	Low	Excellent	Yes	HSS		Good	Low	Baseline Material
A40	Carbide	Flood, H_2O-soluble oi	Good (climb-cut)	Moderate	Good	Yes	HSS		Good	High	Brittle; Requires Carbide Taps
A-390	Carbide	Flood, H_2O-soluble oil	Satisfactory (climb-cut)	High	Satisfactory (very porous)	Yes	HSS		Good	High	Tough, Abrasive Brittle, Requires Carbide Taps
Al/SIC	Carbide/PCD	Flood, H_2O-soluble oi	Unable to machine w/o PCD	Very High (Carbide) Low PCD	Excellent w/ PCD	Yes	Cr HSS		OK Oil	High	Extremely Abrasive, Tap life short

TABLE #3: Machining Parameters

Mat'l/Type of Cut/Tool Type	RPM	Feed	Direction	SFPM	Chipload
A-40 Roughing					
3/8Ø, 4 Fl, TiNiCarbide EM	4,000	10 ipm	Climb	392.7	.0006/tooth
1/4Ø, 2 Fl, TiNiCarbide EM	3,500	20 ipm	Climb	229.1	.0029/tooth
1/8Ø, 2 Fl, Carbide EM	3,000	10 ipm	Climb	98.2	.0017/tooth
A-390 Roughing					
3/8Ø, 4 Fl, TiNi Cobalt EM	3,000	20 ipm	Climb	294.5	.0017/tooth
1/4Ø, 2 Fl, TiNiCobalt EM	3,500	20 ipm	Climb	229.1	.0029/tooth
A-40 and A-390 Finishing					
3/16Ø, 2 Fl, Carbide EM	3,500	20 ipm	Climb	172.3	.0029/tooth
1/8Ø, 2 Fl, Carbide EM	3,000	8 ipm	Climb	98.2	.0013/tooth
1/16Ø, 2 Fl, Carbide EM	4,000	5 ipm	Climb	64.9	.0006/tooth
1/32Ø, 4 Fl, Carbide EM	5,000	3 ipm	Climb	41.9	.0002/tooth
3/16 Ø, Center Drill	3,500	2 ipm	--	--	--
.100 Ø Drill	3,500	2 ipm	--	--	--
1/4 Ø x .03 Thk. T-slot cutter	2,500	5 ipm	--	--	--

The packages are placed in a simple copper fixture (Figure #2, above) that constrains the FT's and preforms in their socket-holes. Figure #11 shows a macrophotograph view of both wound wire and stamped flat preforms. The assembled fixture, loaded with the package, preforms and FT's, is placed in the graphite heater-cavity of a DAP 2200 thermal processor and an 18-minute, vacuum-assisted reflow profile is run. Figure # 12 shows a sketch of a fixtured package in the graphite heater cavity of a DAP 2200 system.

Solder Composition

The solder chosen is an old semiconductor die-bonding standby: 80% Au/20% Sn, liquidus 280°C. We used both wound-wire preforms and purchased flat-washer preforms. In some cases of looser fit-up we used both types to compensate for a larger than desired fit-up gap.

Reflow Procedure

The process overview is:

- solvent clean FT's, preforms and plated packages in ultrasonically agitated acetone
- blow components dry with house N_2 and store in N_2 drybox.
- assemble FT"s and preforms in solder fixture wearing clean white nylon gloves with clean SS tweezers
- place assembled package/fixture in DAP graphite cavity, close system
- run profile from Eeprom
- remove fixtured package from DAP and then remove package from fixture
- visually inspect, He leak-test package and store for future substrate-attach step

Notes:

Packages were fixtured in one building on our campus and carried to another building in a Pyrex Petrie dish for solder reflow; this is one measure of a robust process.

This is a "green process": no CFC's were used or are needed for excellent solder-joints despite assembly in one building and solder-reflow in a remote location.

Reflow Profile

The solder reflow profile shown in Figure #13, was adapted from a profile developed by Darrell Dickinson of SST, maker of the DAP system. We wanted a relatively rapid heating cycle, we wanted to vacuum-outgas the surfaces of the plated package, the plated FT's and the preforms for some appreciable time at an elevated temperature just below the melting point. This reduces the tendency to form gas bubbles in the molten solder. Table #4 shows some common solder alloy physical properties. We reflowed our preforms in flowing house-N_2 as the fixtured part temperature rises to the 280°C melting-point of Au/Sn solder.

An improvement might be to reflow in pressurized N_2 to further collapse gas bubbles in the molten solder joint. Another fillip might be to use 3% H_2/97% N_2 forming gas. This somewhat reactive gas might help further clean all the surfaces to produce cleaner joints and promote even better solder flow.

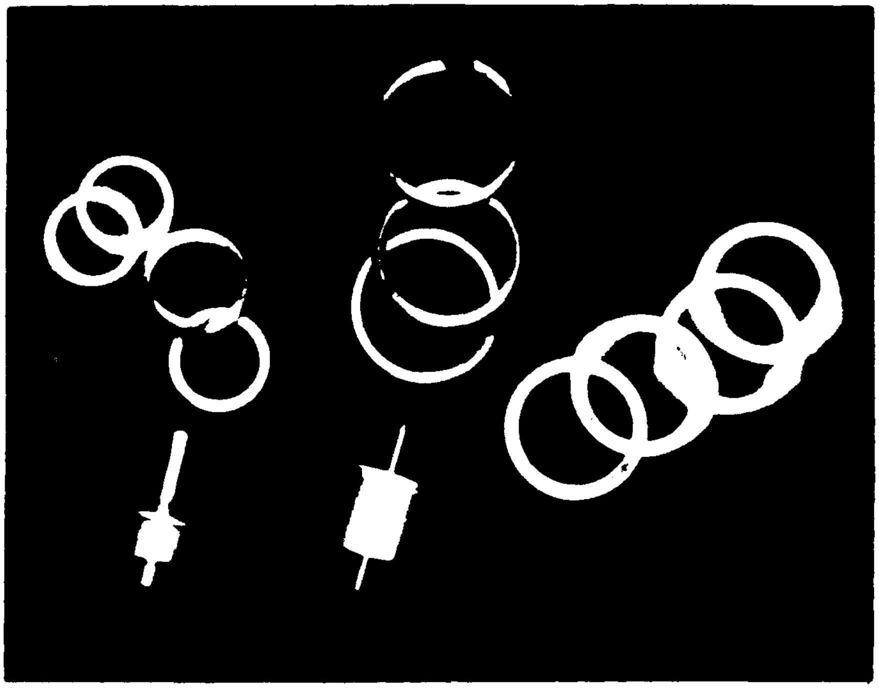

FIGURE 11. Array of Au/Sn Preforms, Wound-Wire and Stamped Flat Washers and FTs.

FIGURE 14. Various Al-Based Custom Hybrid Microwave Packages.

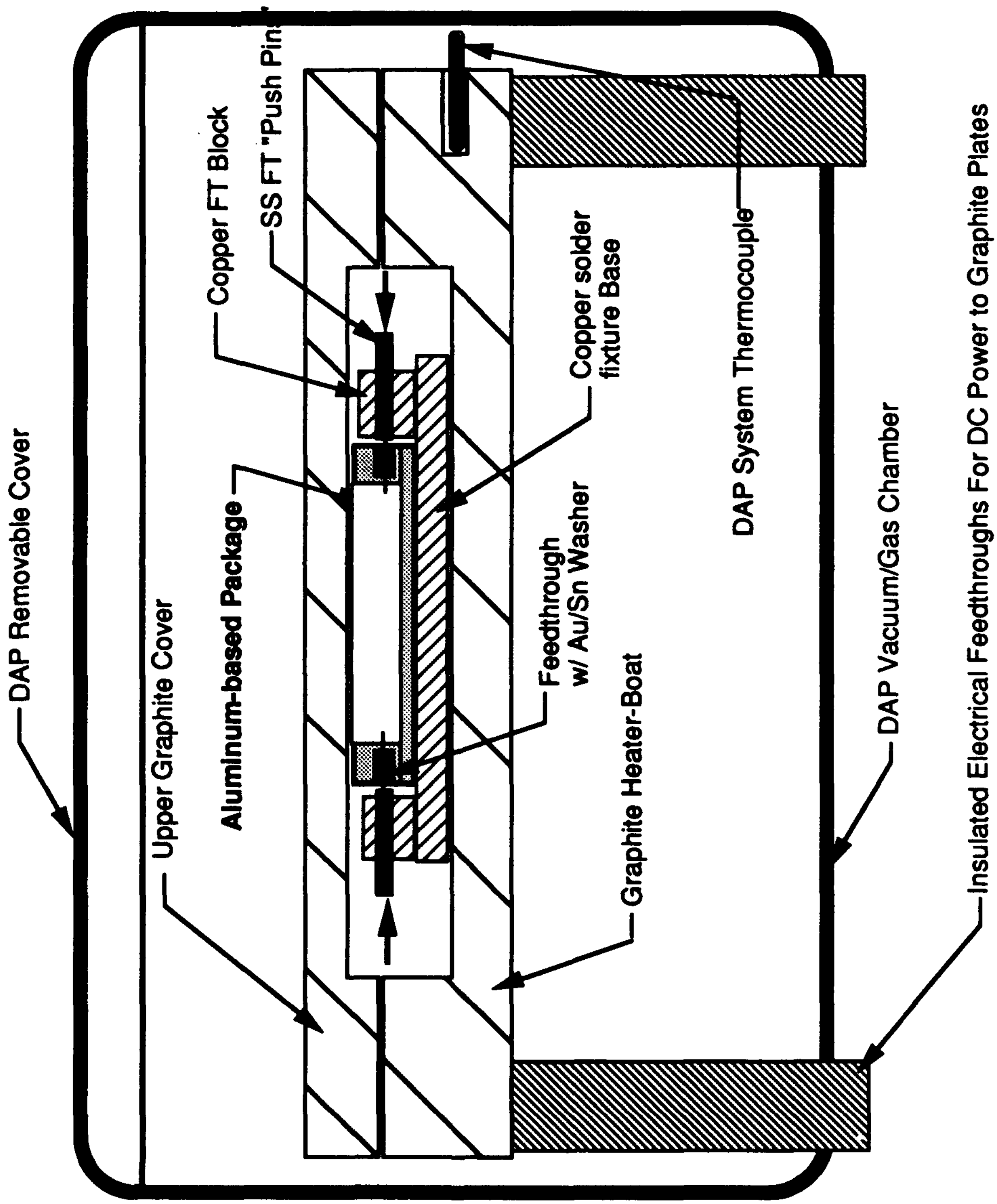

Figure #12: Cross-Section of Fixtured Package in DAP Graphite Heaters

FIGURE # 13: DAP 2200 Thermal Profile

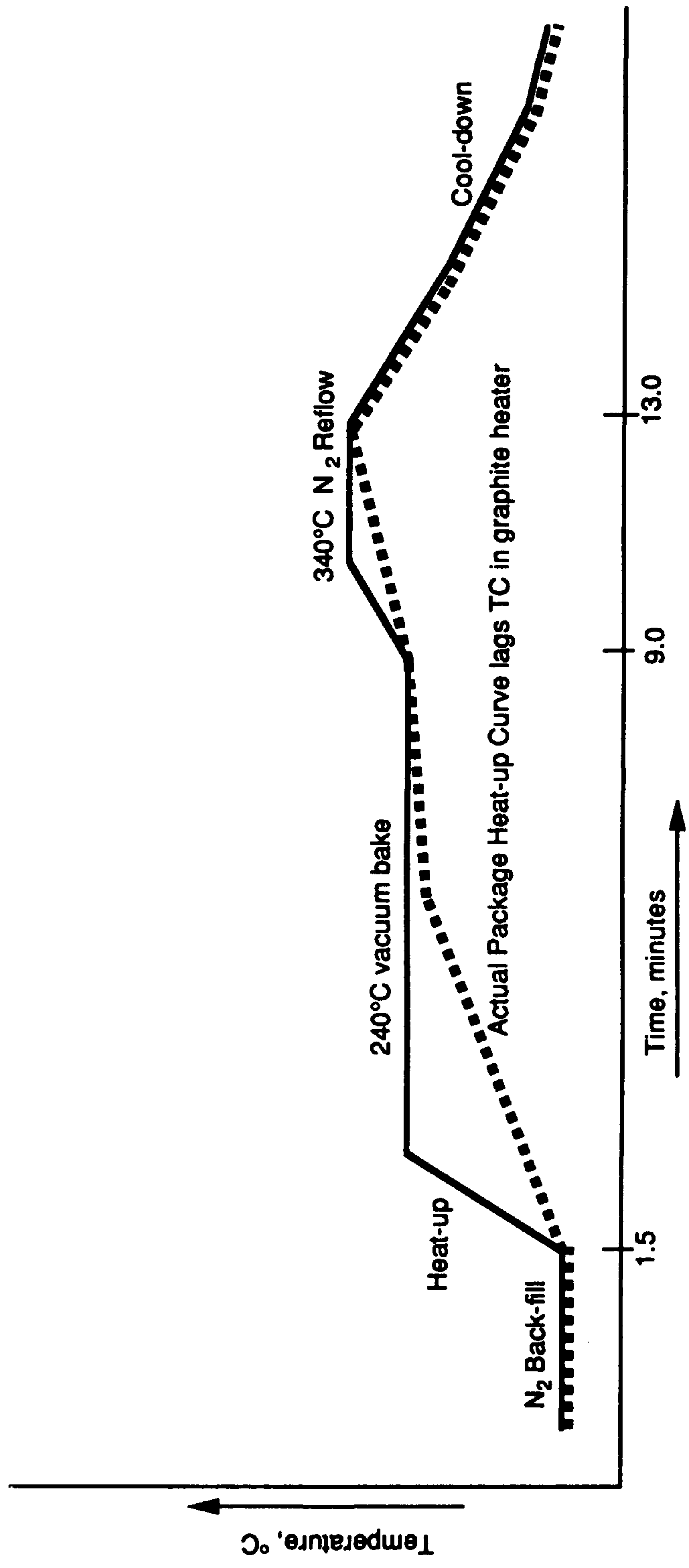

TABLE #4: Solder Alloys Composition and Melting Point

Solder Description	Composition	Melting Point	Flux Required	Maskant Required
Gold/Tin Solder	80%Au/20%Sn	280°C	no	no
Gold/Germanium Solder	88%Au/12%Ge	365°C	no	no
Sn96 Solder	96%Sn/4%Ag	230°C	yes	yes
Sn63 Solder	63%Sn/37%Pb	182°C	yes	yes

Removal and Replacement of FT's

Using Kestor's high-temperature #1587-HT flux, and Sikama's linear μ-processor-controlled hotplate, we were able to remove a "bad" FT from a test package and replace it with new FT, maintaining full open-face package hermetic integrity. Alpha Metals 564 Reliasolv[R] solvent was then used to immediately remove all traces of the flux. This is a somewhat involved process and will not be fully detailed here.

Joint Design Discussion

16 6061 "Model Packages", 16 A-40 "Model Packages", 9 selectively reinforced BP "T/R Modules", one DWA bulk-reinforced "box-package" and some 30+ program-specific Integrated Microwave Assembly, "IMA" packages, were populated with in-house fabricated, matched-glass FT's using the DAP profile shown. We worked through some solder-joint design problems on the path-finder 6061 Model Packages and developed tolerancing/preform-volume guidelines for solder joints in aluminum materials. These lessons are being successfully applied to A-40 and Al/SiC packages that are now in-work.

Results and Conclusions

16 6061 Model Packages, 16 A-40 Model Packages, 9 selectively-reinforced Al/SiC T/R Modules and one bulk-reinforced Box Package had a total of 122 FT's installed. A sixth and smaller 6061 Al package, the smallest shown in Figure #14, had been designed, fabricated and populated with 3 FT's each in an earlier Au/Sn solder study performed in 1990.

This earlier Au/Sn solder effort had emplaced 36 in-house matched-glass FT's in 12 smaller 6061 plated-aluminum IMA packages using the same preforms and joint fit-up but using Kestor's 1589-HT flux. These FT's were solder-reflowed on a μ-processor controlled Sikama Linear Hotplate in a 2-minute profile in air. These 12 packages were subjected to the same thermal shock/thermal cycling tests and showed exactly the same excellent results.

Two of the fundamental requirements of this effort were that no solder maskants and no fluxes be used. Elimination of solder masking, flux-application, hand-feeding of solder and subsequent flux/maskant removal and clean-up is a reduction in touch-labor of at least 60%.

Another group of A-40 test-strips and IMA's were populated with some 150+ custom FT's using the exactly the same Au/Sn process, preforms and procedures but will not be discussed in detail in this report. FT's have been emplaced in packages in both the pin-horizontal and pin-vertical orientations in this effort.

When the joint fit-up is properly sized with controlled clearances of approximately .001"-.0015" gap on the radius, no change in leak-rate was seen on any of the 150+ FT's. Packages gave measured open-face He leak-rates in the less-than 1×10^{-9} atm-cc/sec range both before and after 15 thermal shocks, liquid-to-liquid, 10-second-transfer, 5-minute-dwell from -65°C to + 150°C and then a subsequent 100 thermal cycles from -65°C to + 150°C, air-to-air.

Two A-40 Model Packages have now survived 45 thermal shocks and 300 thermal cycles and 45 thermal shocks and 400 thermal cycles with no change in He leak-rate. These two packages are still in the less than 1×10^{-9} atm-cc/sec He range. We routinely see no measurable He leak-rates on any of 2 DuPont #120 SSA's and one Veeco Model #170 leak detectors with both direct-glassed Kovar packages and in any of these aluminum-based packages with Au/Sn-installed FT's.

The PCD-machined 55 vol-% Al/SiC are plated and ready for FT emplacement. The copper solder fixture specification is detailed, ready for fabrication. Two of these units have been passed forward in the assembly process to verify laser lid-weld to the clad 6061 sealing surface. The diecast 65 vol-% driver modules are in-queue to be finish-machined and plated for FT emplacement in the same solder fixture.

Figures #15 and #16 show two different approaches to preform placement during mechanical assembly. We recommend the latter for greater ease of assembly and uniformity of reflow.

Cross-sections through the FT's, as shown in Figure #17, show excellent wetting throughout the solder joint volume; the joints are not uniformly bubble-free, but are certainly RF-acceptable and He leak-free. Figure #18 shows a macrophotograph of a fluxed Au/Sn FT meniscus. Figure #19 shows a macrophotograph of a non-fluxed Au/Sn FT meniscus.

Conclusion

Solder attachment of a low C_{TE} material such as Kovar, to even a high-C_{TE} material such as 6061, can be readily and routinely accomplished and will withstand the severe stresses of successive thermal excursions from room temperature (RT) to -65°C to +150°C and back to RT for an impressive "duty cycle" with no hint of loss of hermeticity.

The tooling or fixturing costs are modest, the labor cost of mechanical assembly is modest. The elimination of the need for hand-applied solder-masking, hand-applied flux application, hand application of solder and then flux removal, followed by maskant removal, is eliminated.

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FIGURE # 15: FT Au/Sn Solder Assembly Prior to DAP Reflow

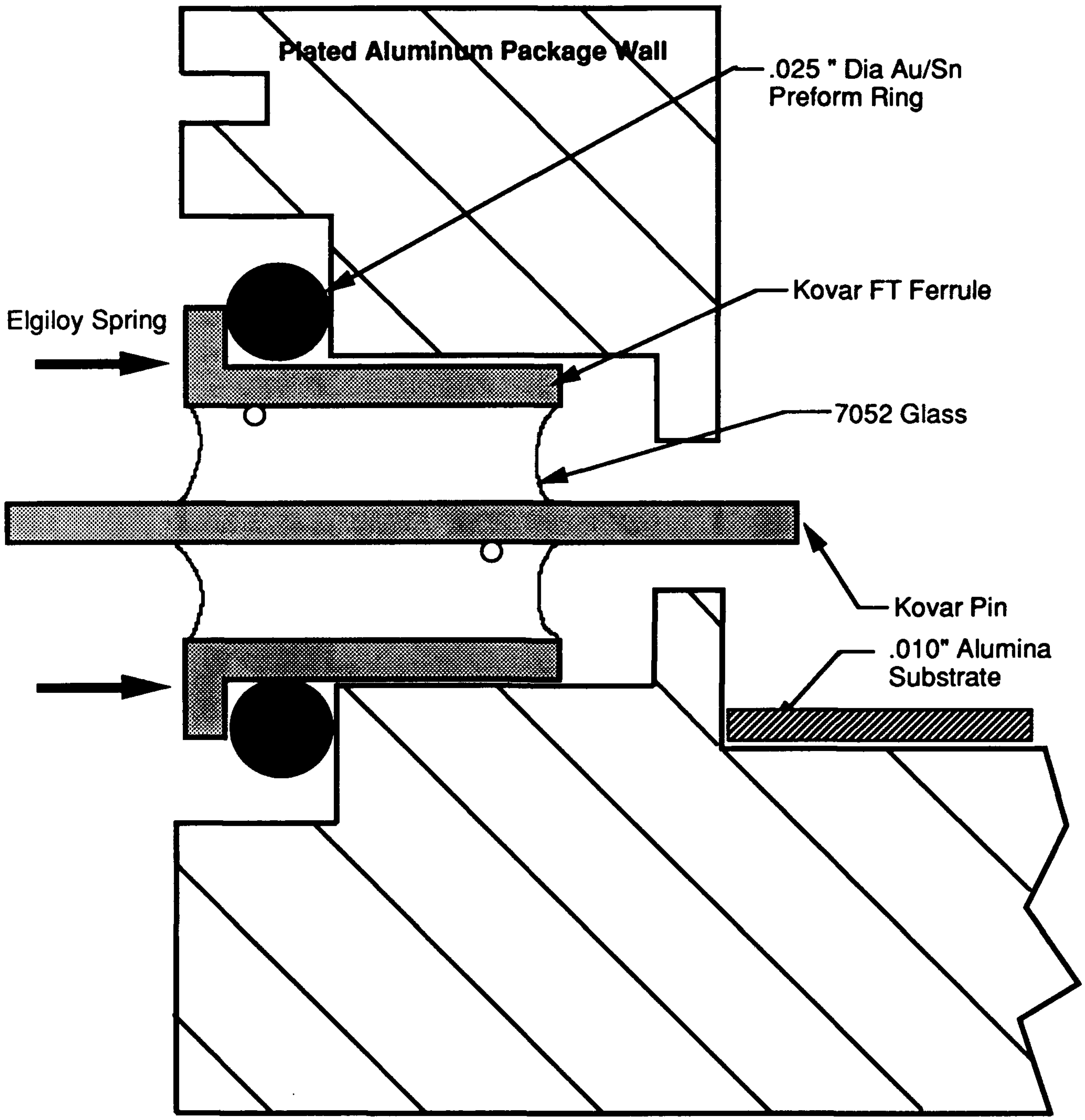

FIGURE #16: Alternate FT Au/Sn Solder Assembly Prior to DAP Reflow:

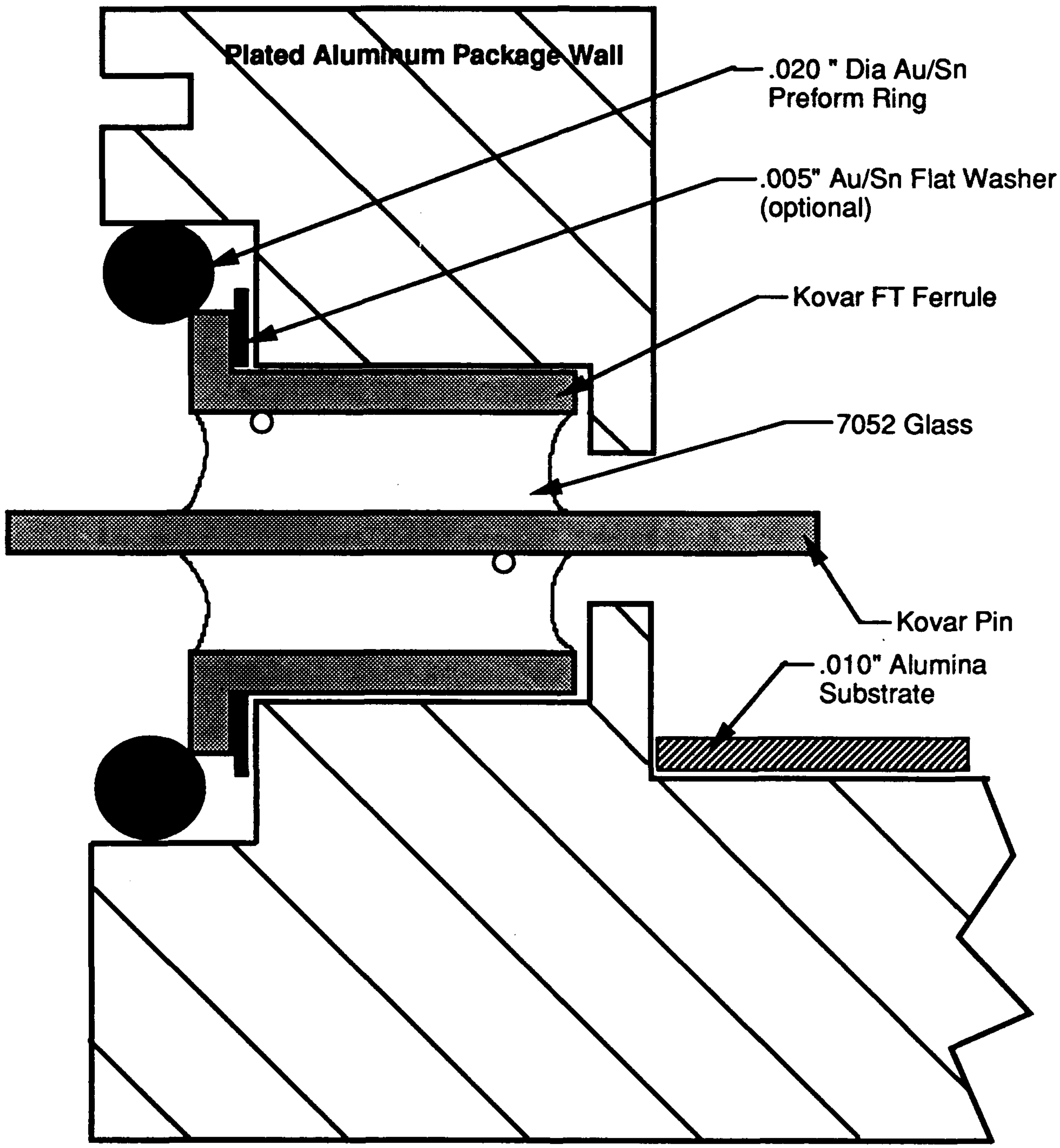

FIGURE 17. Macro Photograph of RF FT Cross Section Showing Au/Sn Solder Joint Fit-Up.

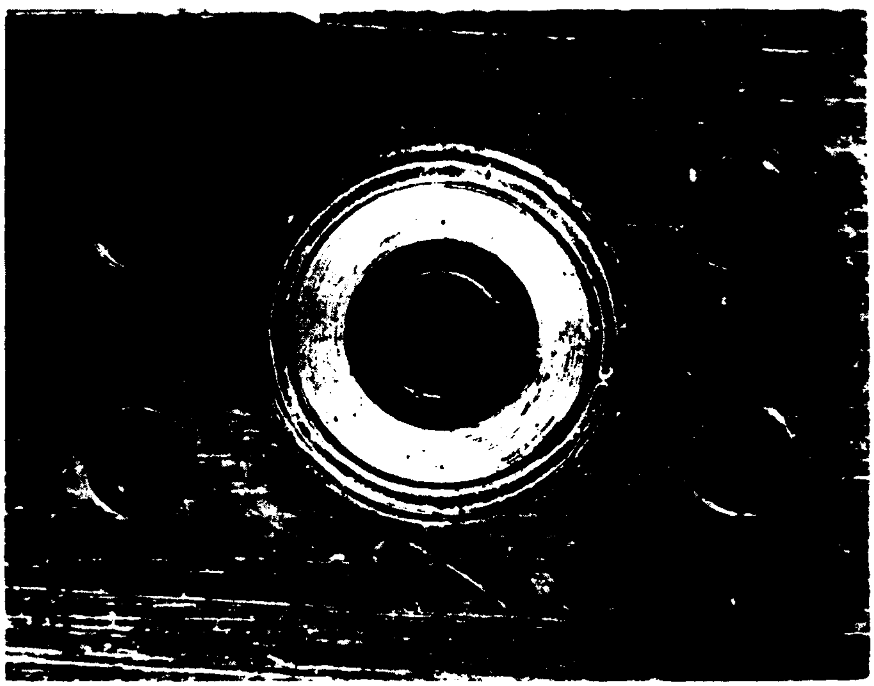

FIGURE 18. Normal Macroview of RF FT Showing Excellent Au/Sn Meniscus Formed With Kester 1589-HT Flux in Air on Sikama Linear Hotplate, 350°C (Nominal).

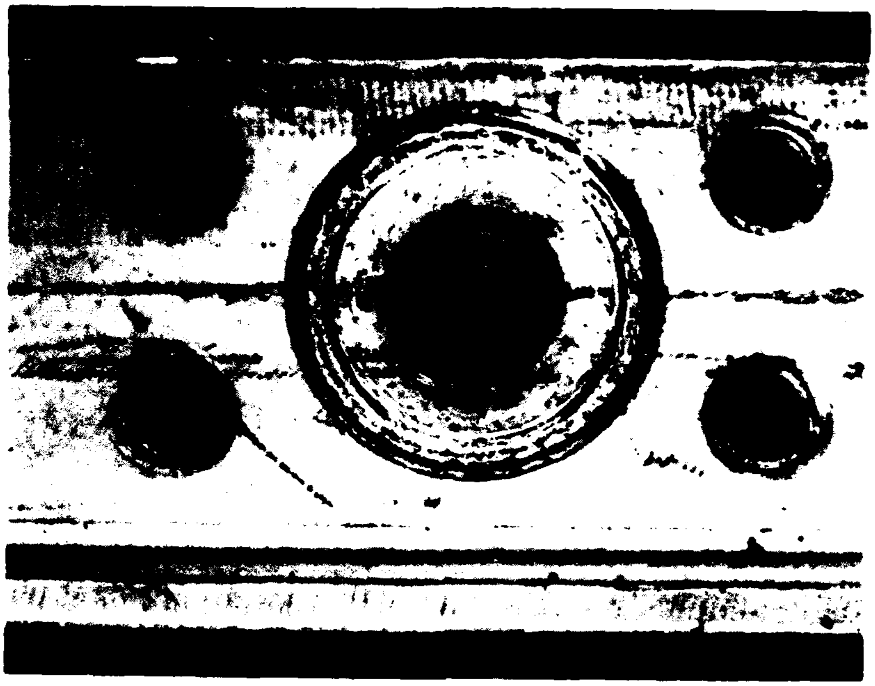

FIGURE 19. Normal Macroview of RF FT Showing Excellent Au/Sn Meniscus Formed in DAP 2200 Thermal Processor Without Flux, in N_2, 325°C (Nominal).

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AN AGGRESSIVE APPROACH TO ODC ELIMINATION

by

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ABSTRACT

The soldering specifications will change to allow ODC-friendly and solvent-free processes. However, the Clean Air Act of 1990 will require product labeling in May of 1993 for products manufactured using class I ODC materials. Environmentally responsible manufacturers will not wait for the specifications to change. This paper describes the technical approach and cultural experiences of Motorola's Tactical Electronics Division with an effort to eliminate all ODC usage in advance of the May 15 deadline for product labeling. Process changes include alternate solvents and no clean processing for wave soldering, reflow soldering, chip-on-board, and hand soldering. The wave soldering effort with Sandia and Los Alamos National Laboratories was reported at last year's Electronics Manufacturing Seminar. With the exception of space flight hardware, optical assemblies and chip-on-board products, acceptable solvent-free solutions have been found for all products.

BACKGROUND

The list of solvents and fluxes used in the electronics industry is changing dramatically. President Bush's aggressive commitment to elimination of chlorofluorocarbon (CFC) production by the end of 1995 has driven the electronics industry to find replacements for CFC-113 in cleaning operations. In addition, the Clean Air Act as amended in 1990

requires that products manufactured using ozone depleting chemicals (ODCs) be labeled after May 15, 1993. Alcohol is an allowable solvent, but is also a flammable hydrocarbon which is difficult to use in mass cleaning operations. In addition, alcohol is a volatile organic chemical (VOC), emissions of which must be monitored by local environmental quality agencies. Electronics manufacturers can either select alternate cleaning materials and purchase the required cleaning machinery, or can use solvent-free processes.

Motorola has an aggressive commitment to elimination of the use of both CFCs and ODCs. The corporation has established a goal to eliminate the use of CFCs by the end of 1992, and to eliminate the use of ODCs in order to eliminate the need to label products as required by the Clean Air Act. The Tactical Electronics Division has eliminated the use of CFCs and is well on the way to eliminating ODCs. The types of products impacted by this change are electronics manufactured for the NSA, NASA, DoD, state and federal government, and commercial products. This paper outlines the methodology used to achieve these results and chronicles some of the issues which were found.

CFC ELIMINATION

Motorola's initial effort to eliminate CFCs began with a conservation program in 1988. Degreasers were outfitted with stills to recover fluorocarbon vapors, thereby minimizing emissions. The conservation program was quickly replaced by a substitution effort focusing on changing from CFC-113 to 1,1,1 trichloroethane (TCA) for in-line and batch cleaners, and isopropyl alcohol for hand soldering operations. TCA was selected, since very few programs explicitly required CFC-113 and TCA was allowed by MIL-STD-2000, which was the governing specification for many products. By early 1992, Motorola's Government Electronics Group had eliminated the use of CFC-113 in manufacturing operations.

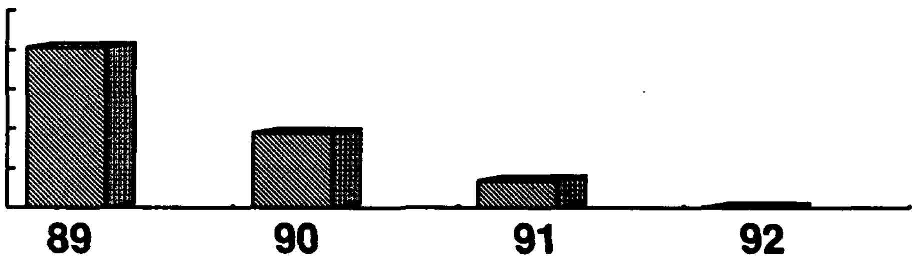

Figure 1. Reduction in Usage of CFC-113 at Motorola GEG.

ODC ELIMINATION PHILOSOPHY

CULTURE AND ATTITUDES

The main barrier to ODC elimination for most contractors will be the cultural issues and attitudes of both their customers and personnel in plant. Whether the approach is to avoid solvent cleaning, or to use a substitute solvent, a significant mental barrier will exist for some people to use these new materials. The process of gaining confidence is not rapid, so the best approach to the cultural issues is to involve everyone in the process early and get a high level commitment in the organization to recognize the need for change. Typical concerns during Motorola's transition have been:

- Amount of residue which will be left on the circuit
- Activity of residues and the long-term impact
- Visual quality and aesthetics - does it look bad?
- General fear of the unknown

The test program described in this paper was developed to answer these concerns. The program included all processes, project representatives and some customers.

ODC ELIMINATION TECHNOLOGY

The elimination of CFCs is simple in comparison to the elimination of ODCs. The alternatives to TCA are numerous. However, none are formally adopted by the military to the extent that they are directly permitted by soldering specifications. MIL-STD-2000A allows alternate solvents, provided sufficient documentation is available to insure that the product reliability has not been degraded. This paper outlines an approach to that documentation, but not all contracts have MIL-STD-2000A as a requirement. Projects must first change over to MIL-STD-2000A to permit the use of other solvents.

Motorola TED has elected to try to bypass the solvent alternatives. The left side of Figure 2 illustrates the preferred path moving from TCA directly to solvent-free soldering. The right side indicates that for special applications, the progression was planned in smaller steps. The materials available in the market today allow a high quality solder joint with little or no visible residue with no solvent cleaning. The materials will also pass all circuit board cleanliness tests and behave well in accelerated life testing (ALT). Cleaning machines are being installed for the specialized applications, but a significant reduction in floor space, energy costs, solvent costs and capital costs can be achieved by totally eliminating cleaning machines.

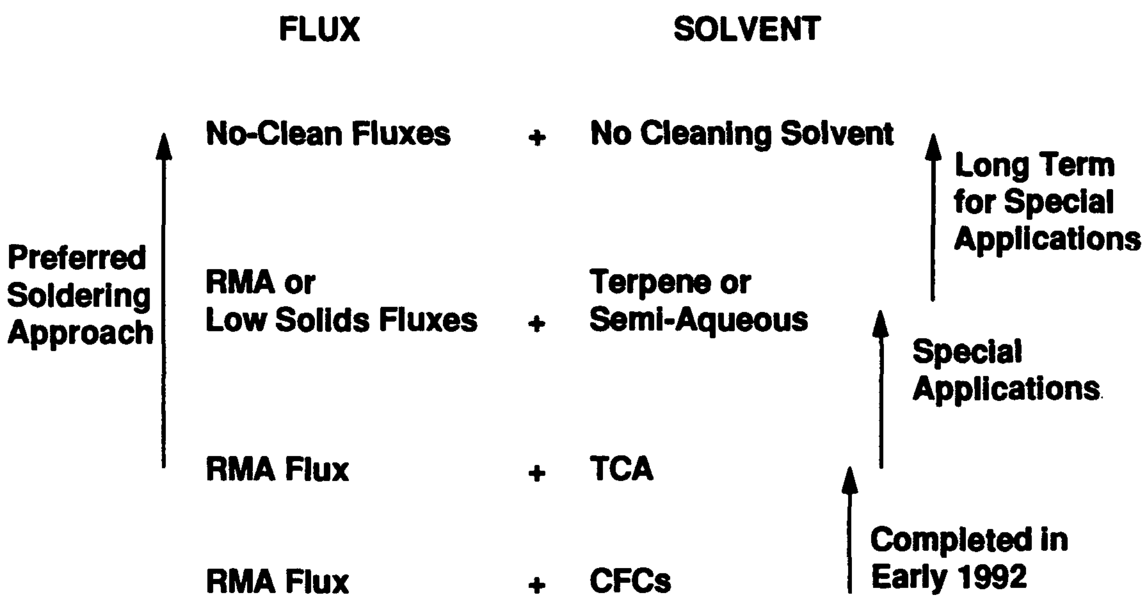

Figure 2. Diagram Illustrating Preferred Path Directly to Solvent-Free Soldering.

PROCESS STANDARDIZATION APPROACH

The elimination of ozone depleting chemicals required evaluating and implementing new materials into the production facility. As new materials were introduced, the processes were first studied to determine the impact. A three step approach was taken to complete this implementation. The process and materials were first characterized, then optimized, followed by standardization. Characterization of the process determined the important variables associated with producing the product. Optimization took these variables and determined the optimum parameters associated with producing the product. Standardization established the process to be used in the production facility.

Reliability testing was another important step in implementing new materials. When trying to eliminate ozone depleting chemicals new materials included soldering materials and cleaning materials. Since the current cleaning process was being eliminated, reliability testing determined that the materials being used on the product did not degrade the function in any way. Residues left from no clean materials or alternative cleaning solvents had to be safe to leave on the assembly and be compatible with parts and materials used to produce the assembly. Reliability tests identified for the

implementation of no clean solders and alternate cleaning solvents were ionic contamination, surface insulation resistance (SIR), and accelerated life testing. These tests were required for many specifications and standards.

PROCESS CHANGES FOR ODC-FREE ASSEMBLY

HAND SOLDERING

Hand soldering is a process in which solder is applied manually and flux residue is removed by hand cleaning with a solvent or in a vapor degreaser. This is an ideal situation for using no clean flux processing. Elimination of this cleaning eliminates solvent emissions as well as employee exposure to solvents. This also provides the opportunity for manufacturing cycle time reduction by deleting a process step.

The objective of the hand soldering evaluation was to prove that the elimination of solvent cleaning after hand soldering produced acceptable solder joints that did not degrade reliability or affect product performance and maintain a ten year storage life. This evaluation included identifying a cored wire solder and flux that could be processed easily without being cleaned.

A preliminary analysis was performed on eight no clean cored wire solders available on the market. Production wire solder was used as a baseline. Ten resistors were soldered to a printed circuit board using each of the no clean solders. The evaluation included ease of soldering, visual acceptability, QQ-S-571 requirements, IPC-SF-818 requirements, and associate comments. Three no clean cored wire solders were chosen for further evaluation based on this matrix.

Five functional assemblies were used for the solder evaluation. These units were disassembled and modified using the no clean cored wire solder and no clean flux. Current production solder and flux was again used as a baseline with one unit hand cleaned and the other unit not cleaned.

After the modifications were made to the units each solder joint was inspected by Quality Assurance. This inspection was performed to evaluate how well the joints could be inspected with the flux residue remaining on the assembly to ensure quality solder joints.

Following inspection the units were put through functional test and then subjected to simulated long term storage testing. During storage testing the units were removed from the chamber at 10 years and 20 years to be functionally tested and inspected to determine the affect of aging. A modified Arrhenius rate equation was used to calculate the long term storage test duration.

Before and after environmental conditioning, a corrosion evaluation including visual inspection followed by surface analysis of any noted residues was performed. Electrical resistance was measured using a four point Kelvin measurement technique through five different solder joints per unit. Two probes were place on the top side of the joints, and two on the bottom side of the joint, and the measured resistance was recorded before and after environmental conditioning.

All the units passed functional testing throughout the entire evaluation. Comparing test data for the initial, midpoint, and final functional tests, the residue on the hardware did not affect its performance. Ninety-eight percent of the joints were readily inspected with residue remaining on the assembly. The amount of residue remaining varied from associate to associate depending on the amount of additional flux added to the solder location. Since the most residue is left during the hand soldering operation, training associates to use less additional flux would be beneficial. The electrical resistance testing showed less than 300 micro-ohms difference before and after environmental conditioning. These results are shown in Table 1.

TABLE 1. Results of Initial Wire Solder Evaluation

CORED WIRE SOLDER	MEETS QQ-S-571	MEETS IPC-SF-818 (TYPE L FLUX)	IPC CATEGORY	VISUALLY ACCEPTABLE (LOW RESIDUE)	EASY TO SOLDER
SOLDER A	YES	NO		YES	NO
SOLDER B	YES	YES	LR3NC	YES	YES
SOLDER C	NO	YES	L3NC	YES	NO
SOLDER D	NO	NO		NO	NO
SOLDER E	NO	NO		NO	YES
SOLDER XX	YES	NO		NO	YES
SOLDER F	NO	YES	L3NC	YES	NO
SOLDER G	YES	YES	LR3NC	YES	YES
SOLDER H	YES	NO		NO	NO
SOLDER XX	YES	NO		NO	YES

COMMENTS:

A. Smells bad - very hard to control - leaves residue
B. Fairly easy to control - sets up slow
C. Does not flow well - requires too much time and temperature
D. Requires too high a temperature - not consistent in the way it flows

E. Fairly easy to control - diameter of solder too large
XX. Flowed easy - did not stick to diameter of leads - solder too thick
F. Flowed slowly - solder too thick
G. Flowed easy - good flow through
H. Flowed poorly - bad flow through
XX. Flowed easy - solder too thick

Ionograph testing was also performed on the no clean cored wire solder samples. Five printed wiring boards were cleaned and subjected to ionograph testing to ensure clean boards. After being soldered the boards again were submitted to ionograph testing. Ionic cleanliness of all boards passed the limits of existing Military Specifications.

REFLOW SOLDERING

No clean reflow is much more process dependent than no clean hand soldering. The no clean paste that is used in a surface mount factory must be safe to leave on the board along with being able to be processed easily. Evaluation included gathering reliability, processing, rheological, and material data. Six no clean solder pastes were chosen for evaluation at the Tactical Electronics Division. Preliminary process experiments included solderability, viscosity measurement, tackiness testing, solder balling, flux spread, and flux loss during reflow. Further evaluation focused on reliability testing including ionic cleanliness, SIR, and accelerated life testing.

Early on in the evaluation it was apparent that the no clean solder pastes fell into a much narrower process window. Reflow profiles used for existing products had to be changed to provide the proper zone parameters for reflow. Reflow atmosphere was suggested by some of the solder paste vendors. Printing parameters were also material dependent and stencil thickness was identified to be an important variable.

Much of the reliability testing performed by the solder paste vendors was confirmed by reflow factories around Motorola Inc. Pilot runs were performed on commercial products at the Tactical Electronics Division. These pilot runs verified the important process variables for no clean reflow. Results are shown in Table 2.

TABLE 2. Results of Initial Solder Paste Testing

	TGA WT%	SOLDER-ABILITY	VISCOSITY Kcps	SOLDER BALLS	FLUX SPREAD	TACK TEST
SOLDER PASTE A	6.1	PASS PASS	1205	0 1 0	15-25 mils	good 4 hours
SOLDER PASTE B	5.8	PASS FAIL	750	2 3 4	10-20 mils	poor < 3 hours
SOLDER PASTE C	3.5	FAIL PASS	1140	1 1 0	20-30 mils	fair 3 hours
SOLDER PASTE D	4.8	PASS PASS	1160	0 0 0	15-25 mils	good 4 hours
SOLDER PASTE E	5.7	FAIL FAIL	1400	0 0 6	10-25 mils	good 4 hours
SOLDER PASTE F	2.6	FAIL FAIL	485	1 20 20	10-15 mils	good 4 hours

Many of the no clean solder paste vendors revised their pastes during this evaluation. Many new pastes became available on the market due to the push to eliminate ozone depleting chemicals. Further evaluation of new no clean pastes is a continuing effort to identify a paste which leaves very little residue and has a wide process window for improved quality. These characteristics are important to the Tactical Electronics Division because of the variety of product types being built.

WAVE SOLDERING

The major effort in wave soldering has been to evaluate and implement a wave soldering process in a nitrogen atmosphere using dilute adipic acid as a fluxing agent. This process is the subject of the first cooperative research and development program between

Motorola and Sandia through the DoE Industrial Waste Reduction Program. An extensive study following the process standardization methodology has concluded that the Seho approach provides reliable electronic hardware that:

[1] Meets the cleanliness requirements for military circuit boards,
[2] exceeds the cleanliness of boards soldered with RMA flux and cleaned in CFC-113,
[3] provides a visual quality level which meets or exceeds current processes, and
[4] has a wide process window.

SOLVENT SUBSTITUTION

Most products will have very minimal technical issues with the progression to no clean materials. However, two main functional areas exist which still require cleaning. The first is chip-on-board products, where the die is bonded to a laminate and wire bonded directly to the circuit board. Due to the sensitivity of the wire bonding process to surface residues, chip-on-board products are still being cleaned in semi-aqueous systems.

The second product area requiring cleaning is space flight and optical hardware. While the level of residue with most processes is minimal, some materials have vacuum condensable materials. Rather than deal with the vacuum condensable residues, these products will continue to be semi-aqueous cleaned. Solvent-free materials are still being evaluated for this application, but no acceptable alternatives have been found.

RESULTS AND CONCLUSIONS

Motorola has an extensive effort to eliminate ODCs from manufacturing processes. This required heavy manufacturing and engineering involvement to evaluate the impact of new processes and materials on our products. A key to the success to date has been the level of commitment of resources to solving the process problems and early involvement of our customers in the testing and evaluation process. In general, most products experienced no technical issues with the new ODC-free processes. The main issues were cultural. In this regard, a top-level commitment of the organization is imperative. Customers will naturally have concerns, and will need to see both good process controls and examples of the new process and materials.

Companies will find this to be a confusing exercise. There are a myriad of new materials on the market, and sorting through the data sheets and vendor claims has been no small chore. Working with customers early on was critical to success in this area, because their technical people face the same proliferation of materials. Processes and materials should be mutually agreeable before being evaluated.

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"A NOVEL VAPOR DEGREASING PROCESS AS A CFC SOLVENT CLEANING ALTERNATIVE"

by

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A serious concern to many people, who have to produce or maintain parts free of contamination, is how to prepare for the upcoming phaseout of two very widely used cleaning products; CFC-113 and 1,1,1-Trichloroethane. A considerable number of alternatives have been proposed and tested to replace these products. While there are a lot of different approaches, most revolve around either avoiding the cleaning operation altogether or involve the use of water as the cleaner and/or the rinse fluid. These approaches are successful for many applications but are not helpful for situations where cleaning is still required but water cannot be tolerated. This paper offers a new approach for meeting those situations.

Past attempts to develop new non-aqueous vapor degreasing type cleaners have been unsuccessful owing to concerns for personnel safety (flammability, toxicity), stability and/or negative environmental impact. A novel cleaning process that avoids these problems has been developed and was introduced at the 1992 International CFC and Halon Alternatives Conference in Washington, D.C. last September. It is believed this process, which has been under development for over two years, will meet the needs of many of these critical cleaning applications that cannot use water. The process uses modified vapor degreasing equipment and is termed Advanced Vapor Degreasing ("AVD")* technology.

Two immiscible liquids are normally employed in the process, each with a different function. One fluid is termed the solvating agent and, as the name implies, needs to have good solvency for a variety of contaminants and does the majority of soil removal. It is normally a high boiling material of lower specific gravity than the other fluid. Some physical properties of a typical solvating agent are shown in Table I.

* Patent pending or Trademark of Petroferm, Inc.

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The other fluid is termed the rinsing agent and serves mainly, but not solely, to rinse or remove solvating agent from the surface of parts. It has a much lower boiling point and higher specific gravity than the solvating agent. Since this is the low boiling agent, and will comprise the vapors in the vapor zone of the machine, it is essential that the rinse agent be non-flammable. Some physical properties of a typical rinsing agent are shown in Table II. Both the solvating agent and rinsing agent are capable of removing particulate matter.

The equipment used in the AVD process is a modified vapor degreaser and is shown schematically in Figure 1. While at a quick glance the equipment sketch looks like a typical vapor degreaser, there are important differences. Both sumps are equipped with recirculating pumps and spray nozzles to both agitate and mix the chamber contents as well as aid in soil removal and rinsing. The freeboard height is greater than normal to minimize losses of rinse agent from the machine. There are also multiple cooling coils in the vapor zone to perform different functions which are to remove the major part of the heat load, chill the vapor to reduce rinse agent losses and dehumidify the vapor zone so the chiller coils can operate more efficiently. Ultrasonic agitation can optionally be used in the rinse chamber, depending on the parts to be cleaned.

The way in which the solvating agent and rinse agent interact in the equipment is quite different from conventional practice. The two agents are immiscible, that is they have no solubility for each other, and under static conditions form two liquid phases. The solvating agent is a very high boiling material and remains in the boil sump much as a contaminant such as flux or oil would do traditionally. The rinse agent has a much lower boiling point and is the only fluid boiling in the sump so that it comprises the vapor zone, the condensate, and finally the fluid in the rinse chamber.

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In operation dirty parts are immersed in the boil chamber where they contact the agitated mixture of solvating agent and rinse agent. The parts are cleaned by a combination of soluble soil removal by the solvating agent and particulate removal by both fluids from the intense agitation of the boiling action and liquid recirculation. Parts are then moved to the rinse chamber where the rinsing agent displaces any solvating agent carried over from the boil chamber. It is important to note that the rinsing action is by displacement, not solubility or emulsification, so any contamination carried in by solvating agent is removed with the solvating agent. After this displacing action the cleaned parts are held in the vapor zone to drain liquid from the surface and then slowly withdrawn from the machine.

The separation of the two functions, solvating and rinsing, allows a great deal of freedom in selection of other agents, particularly the solvating agent. A wide choice of possible materials is available to match different cleaning requirements.

To summarize the essential features of the "AVD" process:

- Cleaning cycle is a dry-to-dry operation.
- Uses modified vapor degreaser equipment.
- Principle equipment modifications are recirculating pumps, extended freeboard and additional cooling/chilling coils above the vapor zone.
- Two immiscible chemicals used, an "AVD" solvating agent and an "AVD" rinsing agent.
- These products contain no stabilizers, inhibitors, surfactants, acid-acceptors or water.
- Both agents are non-ozone depleting, non-flammable and are a low order of toxicity.

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However, it should be noted the solvating agent is combustible and the rinsing agent has global warming properties. Because of the global warming potential the process may be limited to critical applications that cannot tolerate water. In the future the use of HFC's as the rinse agent could greatly reduce this concern and permit wide use, if justified.

The "AVD" process has been operated at several beta sites over the past four to eight months with excellent cleaning results. Also a number of short trials have been carried out using test equipment at our, and others' locations. These also have given generally promising results. Soils removed have been different kinds of oils (transformer, cutting, grinding, honing, etc.), rosin flux and particulate. Cleaning evaluations have compared the "AVD" process cleaned parts with similar parts cleaned by the "current" method, usually CFC-113 or 1,1,1-Trichloroethane. There are now three sites around the country (Florida, Minnesota, Kentucky) where parts can be brought for cleaning tests.

As with most new developments, there was a substantial learning curve to go through in order to get the equipment to operate in a reliable and efficient manner. Current experience indicates the loss of rinsing agent can indeed be controlled to a very nominal amount, so the process economics are not greatly different than for current operation. We appreciate the understanding of those who were inconvenienced by these learning problems and now feel confident we can build equipment to high performance standards.

In conclusion, a new non-aqueous cleaning process has been developed and tested that uses modified vapor degreasing equipment. The chemicals used are non-flammable and non-ozone depleting. Initial cleaning trials indicate the new "AVD" process can clean parts as good as current methods while avoiding the use of chemicals that are scheduled to be phased out in the near future. In properly made equipment the "AVD" process economics look very attractive.

TABLE I

Typical Solvating Agent Properties

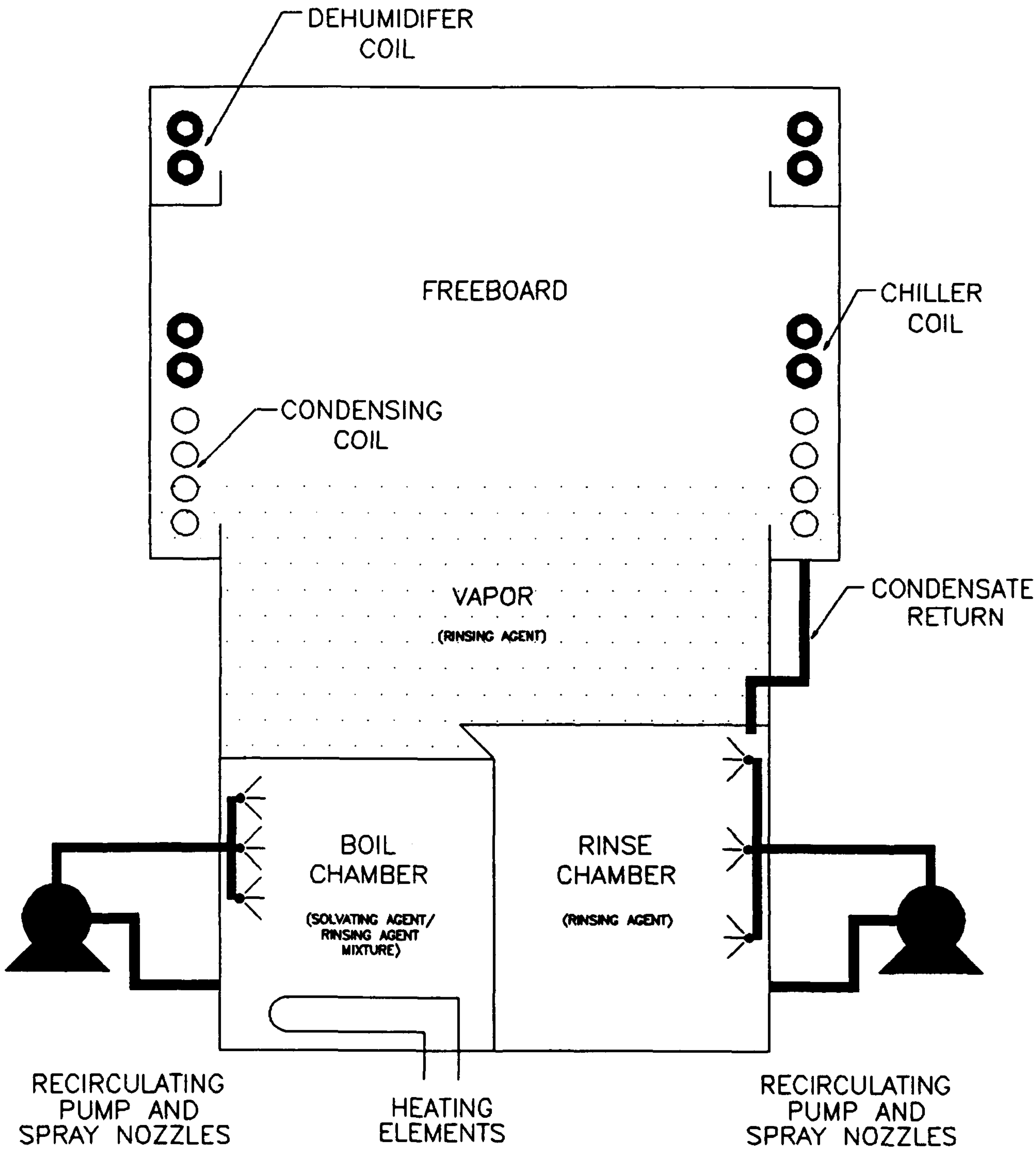
Specific Gravity (25° C)	About 0.8
Closed Cup Flash Point	218° F
Viscosity (25° C)	2.0 - 7.5 cp
Vapor Pressure (20° C)	< 0.1 mmHg
Vapor Density (air = 1)	> 1
Water Dispersible	NO
Compatibility with parts to be cleaned:	Generally good, but should be checked, especially with Polycarbonate, Polysulfone, Polyvinyl Chloride, Polystyrene, Polyurethane, Polymethylmeth-acrylate.

TABLE II

Typical Rinsing Agent Properties

Boiling Point	56^{o} C
Specific Gravity (25^{o} C)	1.68
Flash Point	None
Viscosity (25^{o} C)	0.7 cp
Heat of Vaporization (a+BP)	37.8 BTU/Lb
Inhalation Txoicity (Sub-acute)	Low
Vapor Density (air = 1)	11.7
Surface Tension (25^{o} C)	72 dynes/cm

FIGURE 1
AVD™* PROCESS EQUIPMENT



* "AVD" is a trademark of Petroferm Inc.

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ALTERNATE CLEANING TECHNOLOGY (ACT) THE RAYTHEON INITIATIVE

by

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ABSTRACT

In 1990, the Raytheon Company made a commitment to eliminate the use of ozone depleting solvents in cleaning operations by the year end 1992. In order to achieve this aggressive goal, a multi-divisional team was established to research alternatives, select the best available, and plan the implementation. This report presents the test methodology, the test results, and a discussion of the findings. The tests and conclusions presented encompass; cleaning, performance, long-term reliability impacts, operating costs, health and safety considerations, and environmental impacts.

After a detailed and comprehensive study, the Raytheon team concluded that the best available cleaning process for Raytheon's general electronic cleaning requirement, was a terpene based semi-aqueous process. The factors which lead to this conclusion are complex and many of these factors may be very specific to the requirements of a specific application. The reader is advised to understand these factors before making this conclusion for himself.

Background

Scientists have confirmed that chlorofluorocarbons (CFCs) are depleting the world's ozone layer. The ozone layer protects the earth from ultraviolet radiation (UV-B). Increased UV-B radiation can lead to increased cases of skin cancer and cataracts and has been linked to crop, fish and material damage, as well as to global warming.

It has been concluded that manmade chlorine, primarily resulting from CFCs, is the major factor in a decrease in ozone over Antarctica since 1979.

Uses of CFCs include refrigeration, metal and electronics cleaning, production of insulating foams, automotive air conditioning, and sterilization of medical equipment.

Alternate Cleaning Technology (ACT) Committee

In 1990, Raytheon Senior Management chartered the company to develop a plan to eliminate all ozone depleting chemicals used to clean products. The target date for the completion of this project was the end of 1992. Thus, Raytheon was one of the first to take an initiative and be a leader in eliminating ozone depleting chemicals within the defense industry.

The Alternate Cleaning Technology (ACT) Committee was formed in May 1990 by the Raytheon Corporate Office of Manufacturing and Environmental Quality. The committee consisted of representatives from all the Raytheon Government Groups, thus forming a company wide, multi-divisional initiative.

Due to the wide variety of cleaning processes utilizing ozone depleting chemicals, the ACT committee focused on the common printed wiring assembly (PWA) cleaning processes found at government group locations. Specifically, these processes were defined to be cleaning through all phases of printed wiring assembly and prior to the application of conformal coating. Other applications would be addressed by the individual locations. It was anticipated that non PWA alternative cleaning processes would evolve from the committee's activities. One example is the cleaning of metal fabricated parts.

Definition Of Focus

As a means of achieving a standard method to evaluate all the non-ozone depleting alternatives, focus was placed upon the following specific criteria:

- Must not degrade reliability
- Non-ozone depleting
- Environmentally acceptable
- An effective cleaner
- Safe alternative
- Currently available

Customer quality requirements and specifications were the primary criteria for selection of an alternative cleaning process. All specifications were reviewed and specific requirements were identified as the principal standards for successful cleaning.

Many of the alternatives require process changes and it was expected there would be major capital equipment changes. Therefore, it was necessary to perform evaluations outside of the production environment to prove out process capability on potential alternative processes. The equipment manufacturer must be capable of providing that quantity of cleaning systems necessary to replace existing degreasers in a timely fashion. The equipment manufacturer must also be capable of providing continuing support.

Safety and environmental impacts of the potential alternatives were considered. The process must not present toxic, flammability, or other operating hazards to employees or the community. The waste discharge and waste treatment processes must be environmentally acceptable.

Finally, the cost of the alternative was considered. Non-recurring capitalization, installation costs, and recurring operating costs must be understood and justifiable.

Potential Alternatives

Potential alternatives were classified as follows:

Near Term Possibilities

Near term possibilities were classified as available for immediate incorporation into the manufacturing environment. There were two technologies within this category: semi-aqueous & aqueous.

Semi-aqueous technology utilizes citrus, pine or petroleum based cleaners followed by a water rinse. Several commercial PWA manufacturers have successfully implemented this type of cleaning into their production environments. Current data indicates these cleaners have superior cleaning performance to CFCs.

Aqueous cleaning technology incorporates saponified water as a means of cleaning. This technology has an established history particularly in the metal parts cleaning industry. However, it has limited historical success for removing mildly activated rosin (RMA) flux to the Defense Department cleanliness specifications.

Future Possibilities

Future considerations were classified as not readily available for immediate incorporation into the manufacturing environment. For example, inert atmosphere soldering will impact the entire printed wiring assembly process from procurement of components to the actual assembly process. Further development in surface mount solder paste will be required for this type of soldering to be utilized in high volume soldering applications. Another future consideration involves the use of no-clean fluxes. These fluxes have a minimal historical base and pose concerns relative to long term reliability and conformal coat compatibility.

Ruled Out Possibilities

Hydrochlorofluorocarbons (HCFCs) were eliminated from consideration. HCFCs were added to the Montreal Protocol at the 1991 London meeting due to their ozone depleting potential. The resolution calls for their use only where alternatives are not feasible, with phase out by 2020, if possible, and not later than 2040.

ACT Objectives

In order to achieve the ACT plan of full production implementation of a non-ozone depleting cleaning process for PWAs, the project was divided into two phases.

The objective of Phase I was to evaluate those near term alternatives chosen as candidates based upon the established criteria. Utilizing a controlled test procedure, the ACT committee evaluated the candidate processes based upon their ability to effectively remove rosin flux (type RMA). Specific measurable criteria were established as minimum requirements for successful cleaning.

Phase II of the plan was to perform detailed reliability and qualification testing on the processes selected from Phase I. Although not originally a specific objective of Phase II, the evaluation of closed loop rinse water treatment was added.

Summary Of Phase I Activity

The conclusions and recommendations of Phase I are based upon testing performed on twelve cleaner/equipment combinations, including a control (13 total combinations). Of these combinations, seven were considered semi-aqueous (including the control) and six aqueous. All combinations plus batch and in-line equipment were evaluated. There was one individual unsuccessful batch/aquecus combination. This combination failed visual inspection after several attempts to optimize the process changing the equipment parameters and increasing the cleaner concentration.

Specifically, 900 specially designed printed wiring boards were assembled with 10,000 components and 300 connectors. These PWAs were cleaned to a baseline cleanliness level utilizing a 1,1,1-trichloroethane, de ionized water and isopropyl alcohol cleaning process.

Each PWA was processed through a cleaner/equipment combination using a detailed, controlled test plan involving assembly of thru-hole components, surface mount components, flux application, and wave flow soldering.

Phase I Test Results Discussion

The performance of the vendor equipment/cleaner trials was evaluated by comparing test results to the baseline or control (A) test results. The equipment/cleaner combination was considered to be an acceptable cleaning system if its test results were "as-good-as" or "better than" the baseline test results.

Visual Inspection

Visual inspections were performed to identify flux residues or other contaminates or conditions which may have resulted from the equipment/cleaner combinations. For printed wiring assemblies built in accordance with DOD specifications, no visible flux or flux residues are allowed after cleaning.

In order to quantify and compare visual inspection test results for the equipment/cleaner combinations a rating scale was developed. The rating scale was based upon the amount of flux residue visible under components. The scale rating range from 1 or very clean , no visible residue to 5 or failure, heavy residue under >75% of flat packs and chip capacitors. Table III-1 presents the initial and post Surface Insulation Resistance (SIR) visual inspection ratings for the baseline and equipment/cleaner combinations in order of increasing visual residue.

TABLE III-1. Visual Inspection Results

Vendor Code	Cleaner	Equip	Visual Inspection Results Initial	Post SIR
A	TCA/H20/IPA	Inline	3	3
D	SA	Batch	1	2
G	SA	Inline	1	2
K	A	Inline	1	2
U	A	Inline	2	2
T	A	Inline	2	2-3
P	SA	Batch	2	3
H	SA	Inline	2	4
FX	SA	Inline	3	4
J	SA	Inline	3	4
L	A	Inline	3	5
V	A	Inline	5	5

* Inspection Key

1 = Very clean, no visual residue
2 = Clean, <50% exhibit light residue under chips and components
3 = Moderate, >50% exhibit light residue under chips and components
4 = Marginal, moderate residue under >75% of flat packs and chips
5 = Failure, heavy residue under >75% of flat packs and chips

NOTE: SA = Semi-aqueous, A = Aqueous

From the initial visual inspection, all equipment/cleaner combinations, except System V, were rated "as-good-as" or "better than" the baseline for the presence of flux or flux residues. Specifically, two semi-aqueous systems (J and FX) and one aqueous system (L) were rated "as-good-as" and four semi-aqueous systems (D, G, P and H) and three aqueous systems (K, U and T) were rated "better than" the baseline visual inspection test results.

The second level of visual inspection was performed after Surface Insulation Resistance (SIR) testing was completed. Visual inspection after SIR testing involved lifting all components with SIR patterns underneath and inspecting for evidence of flux residue. The greatest amount of flux was observed underneath the flat pack and chip capacitor. This was due to the minimal spacing between these components and the test Printed Wiring Board (PWB). The spacing for the flat pack was .005" to .012" and for the chip capacitor was .005" to .007". For this reason, these areas were specifically pinpointed for comparative analysis during the post SIR visual inspection. The same scale rating, as previously discussed, was used to quantify the amount of visible flux residue.

In general, the visual inspection rating for each equipment/cleaner combination increased by one level of flux contamination at post SIR visual inspection.

In general, the test PWAs cleaned with semi-aqueous chemistry were considered to have less visual flux or flux residue at the initial visual inspection level than the PWAs cleaned with aqueous based cleaners. Both batch and in-line systems were able to achieve equal initial and post SIR visual inspection ratings with semi-aqueous chemistry. Additionally, these systems were considered "better than" the baseline at both inspection levels.

Ionic Resistivity

In addition to the "as-good-as" or "better than" criteria for acceptability, the limit for ionic contamination as established by MIL-C-28809 and many other DOD specifications was used. These specifications established ionic cleanliness levels and schedules for testing to assure contamination limits have not been exceeded. Based upon the sodium chloride (NaCl) salt equivalent ionic contamination test a final value of less than 10.0 micrograms NaCl per square inch of board surface area was used. Table III-2 presents the Ionic Resistivity test results for the baseline and the equipment/cleaner combination in order of increasing contamination.

TABLE III-2. Ionic Resistivity Test Results

Vendor Code	Cleaner	Equip	ug NACl/sq. in. Epoxy	Polyimide	Average
A	TCA/H20/IPA	Inline	0.47	0.05	0.26
FX	SA	Inline	0.26	0.04	0.15
G	SA	Inline	0.17	0.20	0.19
D	SA	Batch	0.55	0.00	0.28
H	SA	Inline	0.95	0.84	0.90
K	A	Inline	1.36	0.66	1.01
J	SA	Inline	1.40	0.62	1.01
P	SA	Batch	1.53	0.66	1.10
V	A	Inline	3.68	3.92	3.80
L	A	Inline	4.12	3.96	4.04
T	A	Inline	4.09	4.35	4.22
U	A	Inline	4.22	4.88	4.55

NOTE: SA = Semi-aqueous, A = Aqueous

From the ionic resistivity test results, none of the equipment/cleaner combinations exceeded the MIL-C-28809 ionic contamination specification limit. In general, ionic resistivity test results were very low. Even the highest recorded ionic contamination readings, System U, were less than 50% of the established ionic contamination limit. The epoxy PWAs typically had higher ionic contamination levels than the polyimide PWAs. There were lower average ionic resistivity test results with the semi-aqueous equipment/cleaner combinations than with the aqueous equipment/cleaner combinations. Semi-aqueous, batch (D and P) and semi-aqueous in-line (FX, G and H) equipment/cleaner combinations were considered to have performed equally for the removal of ionic contamination. The higher average ionic resistivity test results for the aqueous equipment/cleaner combinations (V, L, T and U) can be attributed to the lack of de ionized water used in the final rinse cycle.

The test PWAs were assembled and processed under very controlled conditions. Specific precautions were taken to assure only flux contamination was introduced to the test PWAs. Therefore, the only variable designed to be measured was the mildly activated rosin (RMA) flux residues. The relatively high ionic contamination limit established by MIL-C-28809 is based upon handling and production processes that are representative of the manufacturing production environment and were not a factor in this evaluation.

In accordance with MIL-F-12456, RMA flux is required to show "no significant reaction" when tested for halide content (chlorides, bromides and fluorides) using the silver chromate paper test. Therefore, RMA flux residues are not highly ionic and, therefore, would not be expected to exhibit high ionic contamination. Experimentally, a test PWA was fluxed in accordance with this test program (60 seconds completely submerged followed by a 90 second drain off). Then, without being cleaned, this PWA was subjected to the ionic resistivity test procedure. A measurement of approximately 60 micrograms of NaCl per square inch of board area was recorded from the 45 grams of flux deposited. Therefore, as expected, MIL-F-14256, Type RMA gave no significant ionic contamination even in large quantities.

Other large scale test programs designed to measure PWA cleanliness, such as the EPA/IPC/DOD Ad Hoc Working Group program used activated rosin (MIL-F-14256, Type RA) fluxes to obtain a wider pass/fail range for ionic contamination. Initially, the use of RA flux was considered for this program, but was rejected since is was believed that the use of RA flux would not be representative of the Raytheon Government Group manufacturing processes. The flux choice was based upon a survey conducted of the Raytheon Government Group manufacturing processes. From this survey, the highest solids content RMA flux was chosen for the evaluation.

The test method utilized also contributed to the lower ionic resistivity test results. PWAs were tested using an Omegameter 600 R which measures ionic resistivity at room temperature. Conversely, a heated test solution, such as available with the Omegameter 600 SMD would have been more effective for accurate determination of ionic contamination. Additionally, more representative measurements would have been achieved had the individual component leads been cut and the components lifted from the PWB surface. Therefore, the ionic resistivity test results for this evaluation are considered to be representative of the ionic contaminants remaining on the surfaces of the PWA exposed to the test solution. From the post SIR visual inspection results, flux entrapped under components may not have been subjected to the test solution and, therefore, would not have been included in the ionic resistivity measurements.

Organic Residue

The test results from the organic residue testing were used as a relative indicator of residual organic reside remaining on the PWA. In the broadest sense, this can be related to the quantity of flux residue remaining on the PWA. The nature of the test procedure, however, prohibits selective analysis of flux residues, only. Therefore, these test results shall be considered to be a general analysis of remaining organic residue.

The procedure involved complete submersion of the test PWA in the extraction solution which solubilized any organic residues remaining on the PWA. Once the extraction solution was obtained, high performance liquid chromatography (HPLC) was used to separate the extracted residues depending on the polarity. The method is based on the ability of a porous gel and solvent to sort and separate sample mixtures according to the polarity of the components in the sample. When the extract is injected into the HPLC, the extract passes through columns packed with a hydrophobic gel. As the extract residues travel through the packing, some components of the extract interact with the packing material and are retained or delayed while other components, depending on the solvent used, continue to travel through the column either less affected or unaffected by the packing material.

From Table III-3, the relative amounts of organic residue remaining on the epoxy PWAs and the polyimide PWAs are presented. Polyimide PWAs averaged lower organic residues than the epoxy PWAs. This difference may be attributed to the affinity of the epoxy laminate material to the extraction solutions. It was estimated that approximately 10% - 30% of the measured value can be attributed to the PWB material.

TABLE III-3. Organic Residue Test Results

Vendor Code	Cleaner	Equip	Organic Residue Epoxy	Organic Residue Polyimide	Organic Residue Average
A	TCA/H20/IPA	Inline	77	22	50
FX	SA	Inline	76	32	54
D	SA	Inline	83	29	56
G	SA	Batch	95	23	59
J	SA	Inline	107	28	68
H	SA	Inline	105	46	76
P	SA	Inline	128	25	77
K	A	Batch	138	73	106
U	A	Inline	174	85	130
T	A	Inline	172	106	139
V	A	Inline	186	161	186
L	A	Inline	244	127	186

NOTE: SA = Semi-aqueous, A = Aqueous

Additionally, Table III-3 presents the combined averages (relative) of organic residues on the epoxy and polyimide test PWAs from all of the equipment/cleaner combinations in order of increasing organic contaminants. From the data obtained from the organic residue procedure, the PWAs cleaned with semi-aqueous systems, including the control, left less than half the amount of organic residue than the aqueous systems. Even System K, the only aqueous system that performed well in all of the other cleanliness tests, had considerably higher organic residues than the semi-aqueous systems.

Surface Insulation Resistance

Surface Insulation Resistance (SIR) test results were used to evaluate the efficiency of the equipment/cleaner combination in removing flux residue by determining the degradation of the electrical resistance of the test PWAs when subjected to the deleterious effects of high humidity, heat and electrical bias. Raytheon's historical experience with this type of testing indicates that deterioration in electrical properties can be attributed to the absorption of moisture which causes metal corrosion, physical distortion and decomposition of organic material. Further, moisture absorption can be accelerated either directly or indirectly through vulnerable insulating materials, such as, flux residues.

In addition to the criteria for acceptability to be "as-good-as" or "better than" the baseline test results, the following guidelines were used when interpreting SIR test results:

- Initial and final SIR readings shall be equal to or greater than 1×10^{10} ohms.
- During humidity, SIR readings shall be equal to or greater than 1×10^{8} ohms.

For discussion purposes, Table III-4 presents a very condensed view of over 5,000 SIR measurements. Twenty test PWAs were produced for SIR testing from each equipment/cleaner combination (10 epoxy, 10 polyimide). From the four SIR patterns per PWA, five measurements per pattern were recorded. Therefore, 400 SIR measurements were obtained from each equipment/cleaner combination.

Additionally, Table III-4 combines SIR measurements from both epoxy and polyimide test PWAs. Due to specific differences in the chemical and physical properties of these two PWB materials, they are typically evaluated separately. However, for this discussion SIR measurements from both PWB materials have been averaged together. Therefore, this SIR data is considered to be representative of the average electrical degradation of epoxy and polyimide test PWAs when subjected to the effects of heat and humidity after cleaning in accordance with the equipment/cleaner combinations evaluated for this program.

TABLE III-4. Surface Insulation Resistance Test Results

Vendor Code	Cleaner	Equip	SIR Code	SIR Results (log) Min	Max	Ave	Qty SIR Failures
A	Base-line	Inline	I H	10.30 8.00	14.30 12.90	13.66 10.31	0
G	SA	Inline	I H	11.48 8.00	14.30 11.30	12.56 10.26	0
D	SA	Batch	I H	10.70 8.75	14.30 11.60	13.30 10.67	0
K	A	Inline	I H	12.48 8.60	14.30 11.48	13.92 10.60	0
P	SA	Batch	I H	12.48 8.00	14.30 11.60	14.06 10.39	0
J	SA	Inline	I H	10.30 6.48	13.48 11.60	13.17 9.92	16
T	A	Inline	I H	10.60 6.48	14.30 12.30	12.84 9.99	17
U	A	Inline	I H	11.48 7.00	14.36 12.78	13.17 9.63	19
FX	SA	Inline	I H	10.00 6.30	14.30 12.70	13.02 9.83	24
H	SA	Inline	I H	9.70 6.30	14.30 12.70	13.18 10.23	25
V	A	Inline	I H	9.90 5.70	14.00 11.70	12.70 9.65	40
L	A	Inline	I H	11.00 5.70	14.30 11.79	13.79 9.46	61

*SIR Codes

I = Initial Readings
H = Humidity Readings

NOTE: SA = Semi-aqueous, A = Aqueous

Four of the twelve equipment/cleaner combinations, met or exceeded the established guidelines. Systems G, D, K and P had initial SIR readings greater than 1 x 10^{10} ohms. During heat and humidity, no readings less than 1 x 10^{8} ohms were recorded. After heat and humidity, SIR readings recovered to values comparable to the initial readings.

Based upon Raytheon's historical experience with this type of SIR testing, Systems G, D, K and P displayed SIR graphs characteristic of what would be expected of a PWB with clean, uncontaminated surfaces and without conformal coating. Initial SIR readings (IR1) were high. At the initiation of heat and humidity (85^{0}C, 85% RH), an expected differential of approximately 1 x 10^{2} ohms (log 2.00) occurred between

IR1 and IR2. During heat and humidity, the readings remained constant. Final SIR readings, taken after the PWAs equilibrated to 25^{0}C, 50% RH, showed a recovery to their initial SIR readings.

From the SIR measurements, the remaining seven equipment/cleaner combinations displayed SIR graphs which were indicative of PWAs with poor electrical performance. Systems H, V and L had low initial SIR readings, especially on epoxy PWAs, and their final SIR readings did not exhibit the expected recovery to the SIR values before the effects of heat and humidity were experienced. Differentials between IR1 and IR2 were often greater than 1 x 10^2 ohms and SIR values were frequently less than 1 x 10^8 ohms. Additionally, during heat and humidity, SIR readings were low and frequently dropped below 1 x 10^8 ohms or the guideline established as the lower limit of electrical degradation.

Systems J, T, U and FX had marginal SIR performance. Even though initial SIR readings were higher than or equal to 1 x 10^{10} ohms, the final SIR recovery readings were low or less than 1 x 10^{10} ohms. Additionally, these systems performed marginally during heat and humidity as demonstrated by the number of readings less than 1 x 10^8 ohms.

The performance of the equipment/cleaner combinations during SIR testing show good correlation to the initial and post SIR visual inspection test results. The equipment/cleaner combinations with SIR graphs typical of good electrical performance (A, G, D, K and P) also exhibited the least amount of flux residue under the flat pack and chip capacitor components. Conversely, the systems with marginal (J, T, U and FX) and poor (H, V and L) electrical performance exhibited more flux entrapment under these components and therefore, had higher SIR visual inspection ratings.

Phase I Test Conclusions

Chemistry Conclusions

The semi-aqueous equipment/cleaner combinations performed better than the aqueous systems. The semi-aqueous systems demonstrated better cleanliness test results for all of the parameters tested.

- Lower initial and post visual inspection ratings
- Lower ionic resistivity readings
- Fewer remaining organic residues
- Higher initial SIR readings
- Higher average SIR readings during heat and humidity
- Fewer SIR readings less than 1 x 10^8 ohms

System Conclusions

Five of the six aqueous cleaning systems did not perform as well as the semi-aqueous systems. Specifically, ionic resistivity readings were three to four times higher than semi-aqueous readings. During SIR testing, twice as many gross failures and lower average readings were observed. Additionally, higher organic residues remained on the PWAs.

The degree of cleaning was determined to be equipment dependent. This was more evident for aqueous cleaning systems than semi-aqueous systems. Although all the aqueous chemistries were similar, only one piece of equipment could clean well enough to fulfill the test requirements.

Semi-aqueous chemistry was determined to be less dependent on the cleaning equipment. Semi-aqueous chemistry was successful in three out of six trials in both batch and in-line equipment. The successful semi-aqueous equipment enabled the cleaner to flush out the flux from underneath the components. This was accomplished via flushing with sufficient agitation during the wash cycle.

Environmental Findings

Semi-aqueous chemistries can be efficiently separated from water, thus closed loop rinse water recycling is viable.

Semi-aqueous chemistries have the ability to accumulate high levels of contamination before disposal is required. Semi-aqueous chemistry has a lower volume hazardous waste generation than aqueous.

Aqueous wash tanks require frequent dumping, therefore high volume waste streams are generated. In general, aqueous rinse water recycling is more complex than semi-aqueous recycling.

Health and Safety Findings

Semi-aqueous chemistries are combustible but are used at temperatures well below their combustibility point. Additionally, semi-aqueous machines are designed with fire detection and suppression systems.

One tested semi-aqueous and all tested aqueous chemistries contain a glycol ether component. Some glycol ethers have an uncertain regulatory future due to a variety of health concerns.

Semi-aqueous solvents can have a strong odor. Proper ventilation is required.

Cost Findings

Cost conclusions are based upon detailed analyses of the systems considered to be viable from the cleaning, environmental, health and safety conclusions. The cost analysis is a relative comparison based upon the ACT designed test board and standard baseline costs for water and power.

Aqueous cleaning systems have higher operating costs. The majority of the cost is due to frequent chemical changes, high water volumes for waste treatment and high power costs for water heating.

Semi-aqueous cleaning systems have lower operating costs due to infrequent chemistry changes and ability to recycle rinse water.

Recommendations

The following recommendations were made as a result of the Phase I testing:

- Utilize a semi-aqueous system in phase II.
- Perform long term reliability testing including corrosion and humidity testing, thermal shock cycling, material compatibility studies and fungus resistance tests.
- Develop standard operating conditions by establishing machine and chemistry parameters based upon the PWA designed by the ACT committee.
- Utilizing a pilot facility, establish a waste water treatment process(es) by evaluating currently available closed loop recycling technologies.
- Utilizing a pilot facility, develop and perform detailed product qualifications by location.

Phase II

Based on a matrix which included health & safety, environmental, cleaning effectiveness and operating costs, the decision was made to pursue the use of terpene in the Phase II Pilot Facility. This facility was installed in one of Raytheon's manufacturing locations in June of 1992 and included two cleaning systems (one batch, one inline) and two closed-loop rinse water processors.

The facility was started up in June of 1991. The process parameters for the effective cleaning of the test boards were reverified, and all Raytheon locations have performed successful cleaning tests of actual production CCA's.

Testing, at the pilot facility using a variety of CCA's from Raytheon product lines was very successful. Numerous CCA's, including very complex modules that are significant cleaning challenges, were successfully cleaned to meet military specifications. Line speeds in the in-line machine using the test board as a baseline averaged 5 feet per minute, with the rinse water temperature at machine ambient, which averages approximately 95^{0}F, due to the energy addition of high volume pumps. Cleaning of more complex CCA's is accomplished through adjustment of these operating parameters.

Environmental

The process of close-looping the rinse waters in the pilot facility proved very successful. The hydraulic balancing and water quality have been totally acceptable to date. All rinse waters generated from the batch and in-line cleaning systems have been effectively treated and returned to the cleaners for reuse. Due to limited loadings of flux and terpene dragout during the duration of the pilot plant operation, we were unable to quantify the life expectancy of the closed-loop rinse water processors. The units did process over 4,000 CCA's without requiring exchange media changes.

Analytical testing of the rinse waters from the batch and in-line cleaning systems, using Raytheon test boards (4" x 7"), revealed lower than anticipated BOD and COD levels. The batch cleaner "composite" rinse water samples averaged less than 300 mg/l of BOD and COD. It is important to note that the first rinse discharges from the cleaner contain the majority of the contaminants. For example the first rinse (prewash), had a BOD value of 1,250 mg/l and a COD of 8,600 mg/l, while the composite of all the rinses together had a BOD of 140 mg/l and a COD of 275 mg/l. Each rinse discharge in the batch unit is 2.5 gallons, with total rinse water discharges averaging 10-15 gallons per batch, based on the number of rinses used. This data was from a run of 30 Raytheon test boards, 15 on each of the upper and lower racks.

The in-line cleaner rinse water averaged less than 200 mg/l of BOD and COD. These results were produced with the conveyor containing test boards over its entire length. The unit in the pilot facility contains a pumped sump that has resulted in the accumulation of a supernatant layer of terpene. This separation has lowered the terpene burden on the closed-loop rinse water processors.

Stack sampling has been performed on the in-line machine and results are pending as of this writing. A definite correlation can be drawn between terpene air emissions and ventilation flows. Proper ventilation control and interlocking can minimize terpene air emissions. Based on results to date, the majority of terpene consumption in an in-line system is via air emissions and not in the form of dragout from the cleaning tank.

Product Reliability and Material Compatibility

The objective of the Product Reliability and Material Compatibility testing was to determine the effects of the selected cleaners on materials and processes used in the manufacturing and assembly of Raytheon products. The testing was designed to determine immediate manufacturing process concerns, as well as long term effects due to material aging or environmental exposure.

The ACT Phase II Product Reliability and Material Compatibility test plan was divided into the following test groups:

- Thermal Cycling and Humidity Aging
- Long Term Surface Insulation Resistance
- Material Compatibility Evaluations
- Fungus Resistance Testing

All testing was performed on epoxy and polyimide printed wiring board (PWB) material and printed wiring assemblies (PWAs). The test PWBs and PWAs designed for the ACT Phase I test program were used as the testing substrates for these evaluations.

Prior to testing, all PWBs and PWAs were cleaned to a baseline cleanliness level using the existing Raytheon Equipment Division Manufacturing (EDM), Waltham, MA cleaning process. This process incorporated degreasing with 1,1,1-trichloroethane followed by a 2 megohm, elevated temperature, water rinse and a isopropyl alcohol dip.

A control or baseline group of test PWBs and PWAs were processed in parallel with the selected cleaners using the EDM cleaning procedure.

Thermal Cycling and Humidity Aging Test Group

The thermal cycling and humidity aging test group was designed to evaluate the effects of the cleaners on common metals and thermoplastics. Tables II-2 and II-3 list the materials evaluated.

TABLE II-2. Common Metals and Metal Coatings

Description	Specification
Anodized Aluminum	MIL-A-8625, Types I, II & III; Classes 1 & 2; with dichromated seal
Brass	ASTM-B36, ASTM-B121 or ASTM-B124
Bronze	QQ-B-750
Chromated Aluminum	MIL-C-5541, Classes 1a & 3
Electroless Nickel Plating	MIL-C-26074, Classes 1, 2 & 4; Grade A
Passivated Stainless Steel	QQ-P-35, Types II and VI
Silver Plating	QQ-W-343
Tin Plating	MIL-T-10727
Tin/Lead Plating (unreflowed)	MIL-P-81728

TABLE II-3. Common Thermoplastics

Description	Specification
Diallylphthalate	MIL-M-14
Label with Acrylic Pressure Sensitive Adhesive	Various
Lacing, Wax and Elastomeric Coated	MIL-T-43435, Type 1, Finishes B & C
Polyphenylene Sulfide (PPS)	ASTM-D4067
Rubber Based Adhesive	MMM-A-1617, Types II & III
Removable Solder Mask	G377222
Tape, Polyimide Film and Silicone Pressure Sensitive Adhesive	Various
Wire Insulation, PVC & Teflon Coated	Various

The thermal cycling and humidity aging test group was designed to allow for inspection of the materials immediately after exposure to the cleaner, as well as after the effects of thermal cycling and humidity. These tests were performed for the purpose of evaluating, in an accelerated manner, the resistance of the materials after exposure to the cleaner, to the deteriorative effects of high and low temperature extremes plus high humidity and heat conditions. Prior to the exposure of these accelerated test conditions, all of the test PWAs in this group were conformally coated. Also, conformal coating adhesion was evaluated by cross hatch tape testing. Table II-4 identifies the conformal coating materials used in this test group.

TABLE II-4. Conformal Coating (CC) Descriptions

Code Designation	Conf Coat Material	Manuf	Description	Spec
C	CE-1155	Conap	Two Component Polyurethane	MIL-I-46058 Type UR
P	Parylene C	Union Carbide	Vapor Deposition Film	MIL-I-46058 Type XY

Long Term Surface Insulation Resistance (SIR)

Long term SIR testing provided for electrical loading of the SIR patterns until the ultimate degradations of the electrical insulation resistance or failure of the PWB material occurred. This test was performed under the adverse effects of high heat and high humidity. Prior to testing, the test PWAs were conformally coated in accordance with the materials listed in Table II-4.

Material Compatibility Test Group

The material compatibility test group evaluated the effects of thermoset materials, elastomers, marking inks, sealants, and locking compounds after repeated exposure to the selected cleaners. Epoxy and polyimide PWBs were used as the base substrates for applying the thermoset materials, elastomers and marking inks. Silicone materials were evaluated separately, due to the high potential for contaminating the cleaning equipment. Dimensional and weight stability of elastomers and flexibilized adhesives were evaluated using molded cubes. Sealants and locking compounds were also evaluated by exposing nut and bolt assemblies to repeated cycles of the selected cleaners. Table II-5, II-6 and II-7 identify the materials evaluated under the material compatibility test group.

TABLE II-5. Common Thermoset Materials

Manufacturer	Product Designation	Specification/ Program(s)	Description
Ablestik	Ablefilm 504	MSD Programs	Thermally Conductive B-Stage Film
Ablestik	Ablefilm 506	MIS-23229/MSD Programs	"
Ablestik	Ablefilm 566K	G405366, MIS-41428/EDM & MSD Programs	"
Glyptal	C2031	G371539/EDM Programs	Thermally Conductive Flexible Adhesive
Products Research	PCR 1546	5823537/EDM Programs	Low Modulus Polyurethane
Furane Products	Uralane 5753	G371880/EDM Programs	"
Aptek	Dis-A-Paste 2000	5936290/EDM Programs	Thermally Conductive Polyurethane
Products Research	PR 1440	MIL-S-8802, MIL-S-81733/ EDM & MSD Prog	Polysulfide
Epoweld	Hardman	SSD Programs	Rigid Epoxy
Products Research	PR 1422	MIL-S-8802/EDM & MSD Programs	Polysulfide
Conap	Conathane CE-1155	MIL-I-46058, Type UR/EDM & MDS Programs	Two Component Polyurethane Conf Coating
B.F. Goodrich	A-1226-B	MMM-A-1617, Type II/EDM & MSD Programs	One Component Rubber Based Adhesive
Dexter-Hyson	Laminar X500	MIS-14753/MSD Programs	Two Component Polyurethane Conf Coating
Furane Products	Uralane 7767	6195094/EDM Programs	Thermally Conductive Polyurethane
Armstrong Adhesive	C7/W	5823354/EDM Programs	Rigid Epoxy
Stephan Chemical	Stephanfoam 304	5936265/EDM Programs	Polyurethane Foam
Techform Labs	TC-459	S230MA2521P001 orP003/MSD Prg	Flexibilized Epoxy
Castall	Castall 1200-50/SC29 with DC 1200 Primer	MIS-19867/EDM & MSD Programs	Thermally Conductive Silicone
Dow Corning	RTV 3145	MIL-A-46146/ EDM & MSD Prog	One Component Silicone Sealant
Dow Corning	RTV 732	MIL-A-46106/ MSD Programs	"
Dow Corning	RTV 738	MSD Programs	"
Chemtronics	Chemask S	G377222/MSD Programs	Solder Mask
Dow Corning	DC 340	MIS-18130/MSD Programs	Heat Sink Compound
Emerson & Cuming	Eccosil 4952 (with Primers)	G159097/EDM & MSD Programs	Thermally Conductive Silicone
Castall	1200 HTC	MSD Programs	"

TABLE II-6. Marking Inks

Description	Specification
Hysol 50-202BR (Yellow)	5823349
Hysol 50-100R (White)	5823521
Hysol Wornowink with Catalyst A	MIS-37271
Markem 7221 (White)	837623
Markem 7224 (Black)	837623

TABLE II-7. Sealants and Locking compounds

Description	Specification
Loctite 290	MIL-S-46163, Type III, Grade R
Loctite Sealant H	MIL-S-22473, Grade H
Loctite 414	MIL-A-46058, Type II, Class 2
Permabond 101	N/A

Fungus Resistance Test Group

The fungus resistance test group evaluated the potential of the selected cleaners to support fungus growth. Epoxy and polyimide PWB materials were exposed to the selected cleaners. Both process induced contamination and material induced contamination possibilities were evaluated.

Phase II Test Conclusions

The following conclusions were made as a result of the ACT Phase II Product Reliability and Material Compatibility Testing:

- The cleaners and their associated processes did not effect conformal coating adhesion to epoxy and polyimide PWB materials provided adequate drying of moisture removal was accomplished prior to the application of the coating.

- Silicones, low modulus polyurethanes and low molecular weight hydrocarbons (i.e. wax) are effected by semi-aqueous chemistries and the baseline cleaning process. These materials expand, become softer, lose their adhesion properties or are dissolved by the semi-aqueous cleaners, as well as by the current baseline or solvent cleaning process.

- Marking inks applied in accordance with Raytheon processes to PWBs and PWAs were not effected by the selected cleaners and their associated processes.

- After repeated exposures to the aqueous and semi-aqueous cleaning processes, the combined effects of mechanical agitation and heated rinse water caused the surface of many materials to become slightly abraded or etched. This action changed the material's appearance by removing surface gloss, thus producing a slightly duller material. This is an aesthetic effect and had no impact on the physical properties or performance of the material.

- SIR testing under the severe conditions of high temperature, high humidity and electrical bias reaffirmed the criticality of moisture removal prior to conformal coating. Inadequate drying of PWAs coupled with marginal or poor conformal coating coverage will produce corrosion and result in failure under SIR conditions.

- The cleaners did not support fungus growth.

Recommendations

The following recommendations were made as a result of the ACT Phase II Product Reliability and Material Compatibility Testing for using a semi-aqueous, terpene based cleaning process.

- Reliability and qualification testing was successful.

- As with the current baseline/solvent cleaning process, silicones, low modulus polyurethanes and low molecular weight hydrocarbons should be applied to the PWA at the latest possible operation to reduce or eliminate exposure to the cleaning process.

- Proper curing and application of all adhesives, sealants, coatings and marking inks will reduce the potential for material degradation, delamination or other deleterious effects by the cleaning process.

- The ability of semi-aqueous cleaners to dissolve flux is greater than the current solvent cleaning process, therefore, consolidation of several assembly operations could and should be accomplished before cleaning. This will aid in reducing the number of cleaning exposures.

- Due to the mechanical abrasiveness associated with the semi-aqueous cleaning process, the number of cleaning exposures could and should be minimized during the PWA process.

- The most thorough and critical cleaning and drying should be accomplished prior to the application of conformal coating.

Project Conclusion

Based on the detailed study performed on Alternate Cleaning Technologies, Raytheon initiated replacement plans for every application of ozone depleting cleaning solvents.

The following replacement processes have been implemented at Raytheon:

"Cold Cleaning", also known as "Bench Top Cleaning" or "Hand Cleaning"

- Interim cleaning of lightly contaminated electronic assemblies is now performed with brush or dip cleaning using isopropyl alcohol.
- Interim cleaning of electronic assemblies with "more difficult to clean" contamination is now performed with brush, dip, or aerosol cleaning using terpene.
- Metal fabricated parts machined with aqueous coolants are cleaned with saponified water.
- Metal fabricated parts machined with oil based lubricants are cleaned with mineral spirit based solvents or ester based products.
- Cleaning prior to critical bonding operations is performed using acetone.

"Machine Cleaning"

- Electronic assemblies are cleaned in semi-aqueous machines using terpene and D.I. water.
- Metal fabricated part cleaning is performed using saponified water.

Customer Acceptance

One of the most significant hurdles faced by Raytheon in the implementation of these new cleaning processes was in obtaining the approval of customers. Raytheon's "customers" includes all branches of the Defense Department, as well as other companies. Raytheon received strong support and encouragement from the technical representatives of all customers, however, the implementation was significantly impacted by the bureaucratic constraints of contracts and specifications. Industry and the Government need to find more streamlined mechanisms to implement new or improved technologies. New environmental and technological challenges will require faster response from the industry and the Government.

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SMT SOLDERING, IS IT A FLASH IN THE PAN?

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ABSTRACT

I hope that soldering will become a dated connection process because of the hazards involved. The purpose of this article is to address a cheap easily tailored Surface Mount Technology (SMT) connection system. It is a conductive thermoplastic for SMT interconnections. The process can be adjusted for temperature, vibration and conductivity characteristics unlike soldering. The thermoplastic is reworkable and inert. The conductive metal is encapsulated in the thermoplastic. The current SMT problems result from the nature of fabricating solder connections and the disposal of the residues of both the process and the cleanup of the circuit card assembly. The technical alternatives with their advantages and problems are developed for the most practical approach to meet all the product needs. The characteristics required for the ideal conductive thermoplastic is determined. The application system and resulting bond are developed for both pure and mixed technology SMT circuit cards. A method for rework is presented. The requirements to accomplish this with minimum technical, environmental and financial risk is presented.

THE SOLDERING PROCESS

The current process for SMT interconnection is soldering. Due to the problems with lead poisoning various government regulators and politicians have attempted to legislate this system out of existence.

There motivation is that the traces of lead in the environment are poisoning children. They are still trying to find a practical method to remove all lead from the environment and are not willing to stop. The EPA is removing the current cleaning solvents from the work place as a result of the ozone depletion problem. This effort will soon be complete, with a significant increase in the cost for soldering. OSHA is reducing worker exposure to solder fumes, lead particulates and cancer causing agents in the organics, fluxes and solvents in the work place. All of the above efforts are increasing the cost to build electrical interconnections in any circuit card assembly.

SURFACE MOUNT SOLDERING

In the case of a SMT solder connection the only support for the component is the solder in the joint. The connection is always experiencing shear. The SMT solder connection consists of a component lead, solder, copper trace, adhesive and the circuit card substrate, normally FR-4. A SMT solder connection section is displayed in Figure 1. Each of the above components have a different Thermal Coefficients of Expansion (TCE).

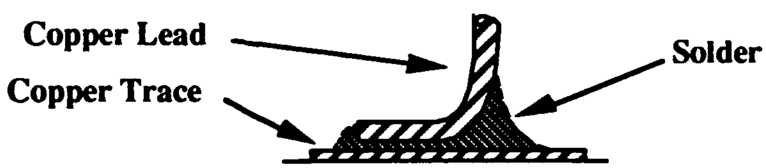

FIGURE 1. SMT Solder Joint

The only temperature where the solder and copper are in mechanical equilibrium is at the temperature where the solder has just solidified. For eutectic solder this is 183°C. For all other solders the temperature is higher. The operating temperature for electronic systems is nominally 20°C with the Mil spec range being -55°C to +125°C. The resulting mechanical shear is significant.

As the electronic circuit card assemblies experience thermal cycling and vibration the solder will work harden. The solder will eventually fracture since it is the weakest part of the connection system. When this fracture occurs it will cause the connection to fail

both mechanically and electrically since there is no supplemental mechanical support.

When the SMT connection bonding material is solder the above strain based failure mode will exist. The reliability of the individual SMT connection is limited by this unrestrained solder fracture mode. On a SMT circuit card there is a significant increase in the total number of interconnections. These factors will reduce the SMT level of intrinsic reliability.

THERMOPLASTIC ALTERNATIVE

Conductive thermoplastics are the optimum class of plastics to generate electronic connections. The initial process will involve the placement and bonding of the conductive thermoplastic to each of the connection parts and then bonding them together. The rework process can use an air gun to melt and open the connection between the component, leads and the circuit card assembly. Once the thermoplastic has melted the component can be removed from the circuit card assembly. A hot air system will evenly divide the thermoplastic between each portion of the connection.

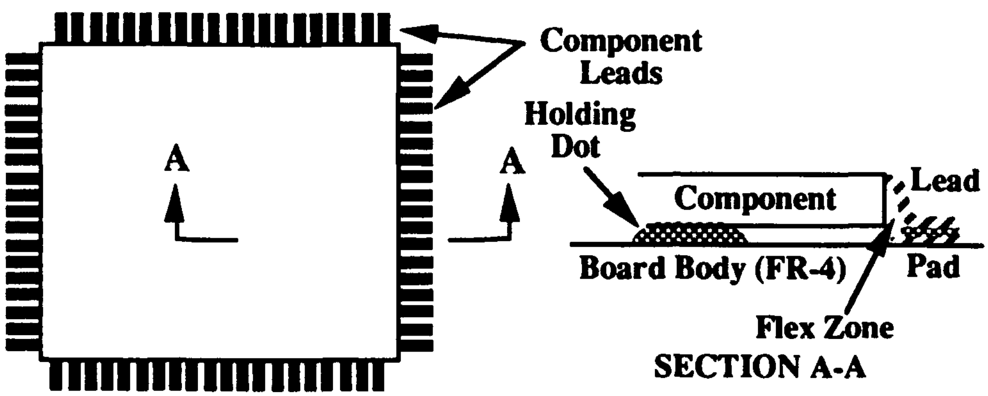

FIGURE 2. Component Attachment

The positioning and holding requirements are the same for assembly and rework. An additional dot of plastic can be used to assist in holding the component in place as required. See Figure 2 for a diagram of this arrangement. The process is practical and economical. The assembly and rework system will tolerate multiple

process cycles without damage to the component or circuit card assembly.

The materials used in conductive thermoplastics are inert. There is no residual heavy metal (tin-lead, solder) or activated chemicals to generate disposal problems. The circuit card starts the assembly process clean and stays clean throughout the SMT process. The use of a conductive thermoplastic system presents a clean process for circuit card assembly activities.

OTHER ALTERNATIVES

Some of the alternatives to conductive thermoplastics are "Z" axis adhesives and conductive cross linking polymers. The cross linking type plastics consist of thermal setting, UV setting, Epoxies and Bakelites. The types of connection under consideration all have the fastening portion of the component lead parallel to the pad surface to generate a reliable connection with low contact resistance and good mechanical strength.

"Z" AXIS PLASTIC

Any "Z" axis bonding system will use a cross linking polymer as the adhesive. Any repair method will require complete removal of the "Z" axis plastic and the component to be replaced. Disturbance of adjacent components is unacceptable. The task will be very difficult to accomplish without damage to the circuit card or violation of the co-planarity requirements of the system. As a result of these problems "Z" axis connection systems are not promising.

A "Z" axis plastic connection system consists of soft balls of plastic that are coated with metal and spaced sufficiently far apart that they do not make contact with one another. In the case of fine pitch connections these balls are about 0.002 inches in diameter. When the connection surfaces are closer than the ball diameter "Z" axis connections will result. The balls can be compressed to 80% of their diameter. This will yield a maximum lead to pad deviation of about 0.0004 inches over the total area between the component and

the circuit card assembly.

Many components are over an inch on a side. The above co-planarity requirement is not achievable for this large an area. This tight tolerance will require some method to deform the circuit card and or the component leads during the bonding process to meet the co-planarity requirement. The residual forces that result will generate accelerated failures. All of the above problems with "Z" axis systems prevent making this an economical and reliable inter-connection system.

CROSS LINKING POLYMERS

The next choice is cross-linking polymer plastics. The rework requirements appear to be a common factor limiting economic utility of any connection system. The field skill levels for rework will be lower than those in the factory. Any plastic that forms a permanent non-reversible connection will present a significant problem for field rework.

Any component that is to be reworked will require all of the bonds for that individual component be opened without damaging the circuit card, adjacent components or the component. A typical example is a 100 plus lead integrated circuit. The opening of all these connections without damaging the circuit card or the component will normally cause damage. This ework problem eliminates all of the cross linking polymer plastics from consideration. These plastics include thermal setting, UV curing, Bakelites and Epoxies.

THERMOPLASTIC REQUIREMENTS

The thermoplastic selection will involve tailoring the cost, melting temperature, mechanics and bonding characteristics to optimize the connection. The TCE of the thermoplastic needs to be greater than that of the copper leads and pads. This generates a compressive force to cause the conductive powder, leads and pads to move toward one another as the thermoplastic cools to operating

temperature. This results in a gas tight electrical connection with uniform resistivity. The majority of the mechanical strains will be locked between the conductive powder leads and pads. This is similar to the process that increases the strength of concrete over the strength of its cement binder.

THERMAL RANGE

The upper limit of operation, storage and the FR-4 glass transition temperatures are about 125°C. As long as the softening temperature of the thermoplastic is above these limits the system will be immune to thermal problems. If the system is to be immune to mechanical disturbances at high temperatures the softening temperature may be moved up. An alternative is to increase the mechanical holding force by placing an additional thermoplastic dot under the component body. See Figure 2. for an example.

The thermoplastic will be tailored to have a eutectic like thermal profile. Eutectic as defined is the characteristic of minimum transition range from solid to liquid. This will allow moving the bonding temperature down towards the upper system temperature without reducing the strength of the bond during high temperature operation or storage. This will reduce the thermal processing temperature requirement during assembly and rework of the circuit card assembly.

REACTIVITY

Thermoplastics are inert throughout their rated operating temperatures. The thermoplastic will be tailored to be compatible with all other materials that come in contact with it during use. The plasticizer can not damage the FR-4 plastic or any other plastic from which the circuit card assembly and the traces are fabricated. Any solvents and cleaning materials used in the mixed technology fabrication process must not degenerate the thermoplastic. The metal selected as the conductive powder must bond to the thermoplastic. This will eliminate deterioration of the finished product.

The mechanical strains will be tailored within the compliant range of the thermoplastic. Cold-flow will also be tailored out for the operating range of the system. The mechanical strength of the thermoplastic is sufficient to generate a reliable connection. The thermoplastic in the liquid phase will wet copper and its oxides for good bonding. Most available thermoplastics meet these characteristics.

THINNING SYSTEM

During paste application the thermoplastic needs to be a thick liquid. If the resulting paste system does not involve a solvent the plastic particulates will only have point contact within the connection area. These voids will cause a weak bond. A thinner system will cure this problem.

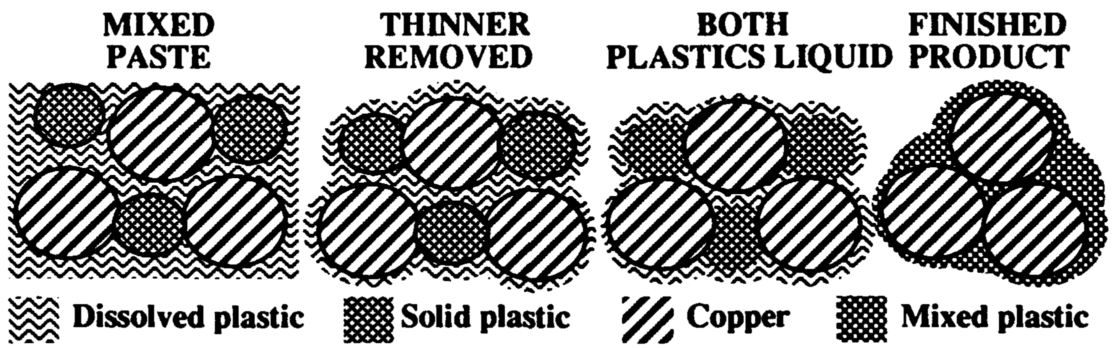

FIGURE 3. Paste Assembly With Thinner

A thinner will dissolve one of the thermoplastics in the tailored blend. Any number of thermoplastics can be used to generate the finished product. The ratio of thermoplastic to thinner will be adjusted to generate good printing characteristics. The least toxic and expensive thinner is preferred. The liquid thermoplastic wets all surfaces. See Figure 3. Once the paste is applied the thinner will be removed from the thermoplastic by heating. this will cause encapsulation of the metal powder, as illustrated. As the process temperature rises one of the plastic constituents will melt and its boundary will form a eutectic blend with the other thereby melting and mixing both plastics. The time involved is short since the migration distance is only few thousands of an inch. There is no voids or trapped gas. The finished product will have good

mechanical and electrical characteristics.

Plasticizer

Thermoplastics use plasticizers to control their mechanical characteristics. This is a part of thermoplastic design. The plasticizer used will have long term stability and compatibility with all the other plastics used in the circuit card and component systems. Any solvents or cleaning materials used in the mixed technology fabrication process must not degenerate the plasticizer. The final requirement for the plasticizer is that it does not migrate out of the plastic during the life of the product.

Thinner Recovery

The EPA, OSHA and other air quality control agencies do not require total removal of the vapors generated during manufacturing. This is becoming a distinct possibility. The volume of thinner involved in SMT connections is small. This can be addressed by using a standard dehumidifier in a closed loop, cross flow drying system. The dehumidifier will add an additional level of control to the drying process. See Figure 4. for an example of this type of thinner recovery system.

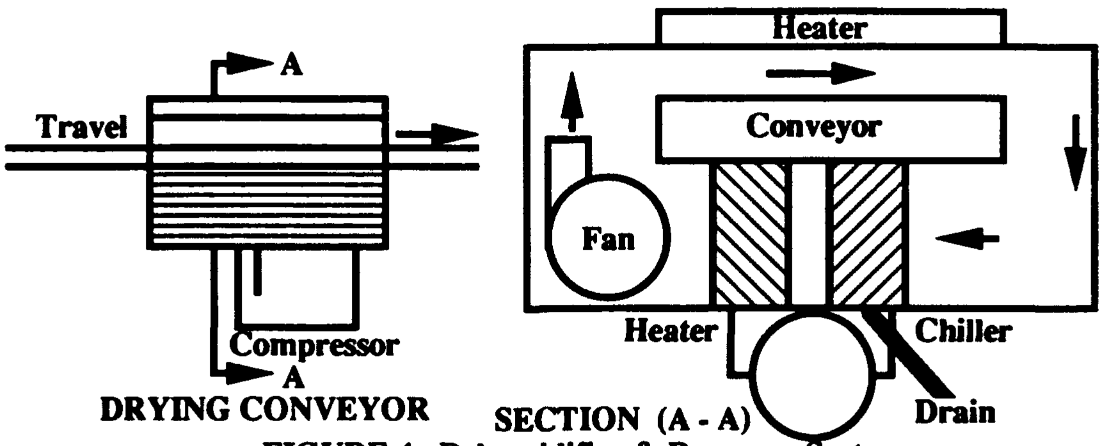

FIGURE 4. Dehumidifier & Recovery System

The wet conductive thermoplastic will enter the heated drying chamber from left to right above. The heater will evaporate the thinner as controlled by the temperature and the vapor removal rate

of the dehumidifier. The fan will drive air across the circuit card assembly. This air will carry the thinner to the chiller which will condense the thinner. The heater will warm the air back to the entering temperature. This process can now be repeated. The rate of removal will be controlled by the cooling rate in the dehumidifier. The process will continue until the thinner has been removed. The reuse of a single charge of air will reduce the energy requirement and pollution potential. The total energy requirement is less than that required to use the air once then vent the contaminated air to the environment.

THERMAL REQUIREMENTS

The processing temperature for conductive thermoplastic is tailored so that the bonding temperature is above the maximum operation and storage temperature and below the soldering temperature. The initial deposition of thermoplastic is accomplished prior the development of oxides on the surface of the circuit card or the component. A small amount of oxide is desirable since it will improve the mechanical bonding of the thermoplastic to the metal components. The thermoplastics TCE will cause penetration of this oxide when properly tailored.

An examination of the connection shows that the thermal forces are less because; the temperature swing is less and the TCE of the conductive thermoplastic is tailored to be just above that of the the lead and pad. In addition the thermoplastic material is compliant which will reduce this problem.

All of the above requirements are tailored for optimum performance. The actual development of the manufacturing processes is beyond the scope of this document.

CONDUCTIVE POWDER SELECTION

The other parts of the connection are copper. Copper is the logical powder material since it will always match its own TCE and is cheap. If the metallic powder chosen is any other metal there is a

problem resulting from the different electrochemical potentials and TCE's between it and the copper leads and pads. Any electrical current through the connection will increase these problems. The thermoplastic bonding material will protect the metal from corrosion.

The conductivity requirement of the connection is determined by comparing the trace resistivity to the pad resistivity. The trace is 5 mil. wide and 0.7 mil. thick in a system with 20 mil. center to center traces. The pads are 10 mil. wide and 35 mil. long. This will yield a 3.5 square mil. cross sectional area for the trace and 350 square mil. cross sectional area for the pad. These areas will allow a 100 to 1 ratio of resistivity with no reduction in the conductivity of the connection relative to the conductivity of the trace. If the resistivity were allowed to reach a value of 1/1,000 that of the trace this would correspond to the an additional trace length of 0.07 inches.

POWDER SIZE

If the metallic powder has multiple sized components the conductivity is improved. The metal packing density is increased. If the mixture is of the 1-2-3 variety as in the fabrication of cement bodies, (i.e., gravel, pea gravel and sand.) the historical development of aggregate characteristics from cement applies. This sizing approach can be scaled to fit the SMT application.

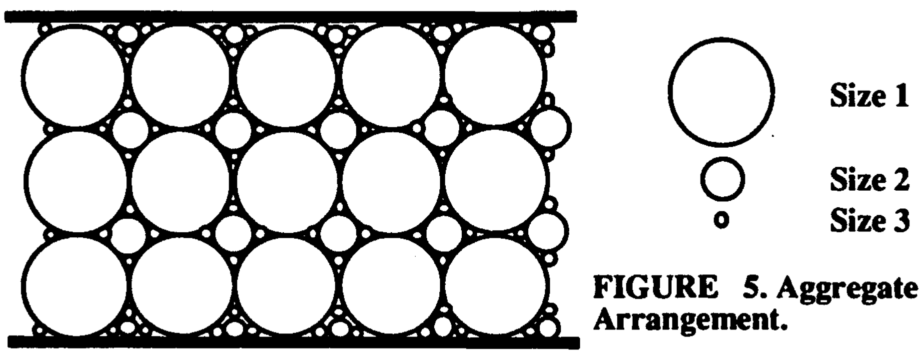

FIGURE 5. Aggregate Arrangement.

The particles will fill the voids between the larger particles for maximum packing density. If the volume of the larger particle occupies 50% of the available volume, size 1 in Figure 5. Figure 5 is a two dimensional representation of a three dimensional system.

There are two additional powders each occupying 50% of the volume of its next larger size. The amount of space left for the thermoplastic binder will be about 20% of the total volume.

In the aggregate system as represented by Figure 5 the number of contact points between the connecting surfaces will be increased by at least 6 times. This will reduce the resistivity of the connection as a function of the parallel connections. Each of the smaller size particles, (sizes 2 and 3), jumper additional points from the next larger particle size to reduce the resistivity of the connection. The common geometry of the particles causes them to have the same resistance independent of size. The connection resistivity is a function of the contact points as well as the size of the individual particles.

A larger powder size will enable better penetration of any surface contaminates. If the particulates are too large they will not deposit uniformly within the body of the connection.

PARTICLE SHAPE

If the particles have a convoluted shape there will be many connection points. The metallic density will be low resulting in low electrical conductivity and strength. Some form of bulky angular cross section will yield the best strength and electrical performance. This has been verified in the concrete industry. Direct mechanical processes will tend to smear the metal. Chemical processes will tend to generate convoluted particle shapes.

TEMPERATURE COEFFICIENT

The final item to be considered in the powder fabrication process is the thermal usage environment of the connection. The pad expansion rate will be modified by the circuit card expansion rate. The resulting average expansion rate will be larger than the expansion rate of the copper lead. The composite material can be adjusted such that thermal TCE closely matches the average of the copper leads and the pad-circuit card combination. This suggests that the final material will have to be copper.

The above requirements, require an empirical tailoring process to find the optimum copper powder for an inexpensive and reliable connection system. The development of the process for these copper based powders is beyond the scope of this article.

BONDING TECHNIQUE

The historical way to make a reliable connection is to apply sufficient glue to generate flow for good wetting action. This is not an option for conductive thermoplastics since it would short out adjacent leads and or pads. Both surfaces can be primed with conductive thermoplastic prior to making the connection. This is accomplished by coating both surfaces prior to the final bonding process. The application of conductive thermoplastic to both surfaces will increase the maximum thickness that can be built.

TCE VARIATION

The probability is that the component TCE will not match that of the circuit card material. An example is a ceramic component package and a FR-4 circuit card. Gull wing leads are shown in Figure 2. ^The shape of the leads provides an easy method to absorb the growth and contraction of the component relative to the circuit card. The cause for this is the temperature swings that the system will encounter. The TCE's for the more common materials used in circuit card systems are in Table 1. These TCE values are non-linear.

MATERIAL	TCE (PPM/°C)
COPPER	16-18
SOLDER	24-26
FR-4, below glass transition	16-22
FR-4, above glass transition	44-60
CERAMIC	6-8
SILICON (I/C's)	3-4

TABLE 1. Material TCE's.

COMPONENT ATTACHMENT

When a component requires additional bonding a small amount of thermoplastic is placed under the component. It is located at the center of the component. The growth and contraction of the component will be symmetrical. This action will flex the component leads which will bend in the knee area identified on section A-A of Figure 2. The thermoplastic can be patterned such that it does not short out any traces on the circuit card and allows the vapor to escape from the component. This is a part of the mixed technology assembly process.

The component TCE can be different from that of the circuit card material. The volume and direction of copper traces within the circuit card will change the TCE in locally. Increasing the volume of thermoplastic under the component will add mechanical support and thermal conductivity to the component. This can be accomplished without adding additional processes to the fabrication of the pure SMT circuit card assembly. The mixed technology system already has a under component attachment process.

SMT CONNECTION PROCESS

The connection manufacturing process will consist of pre-depositing on each surface a paste of conductive thermoplastic. See Figures 6, 8 & 10 for sections of the unfused conductive thermoplastic. The component lead shown in Figure 6 is processed to dry and bond the thermoplastic to the component. See Figure 7 for a section of the thermoplastic, as fused, to the component lead. The drying process may require some form of vapor capturing system for current or future OSHA or EPA requirements. See Figure 4 for an example.

The layer of conductive thermoplastic protects the connection surface from further contamination. The components can be handled prior to final assembly.

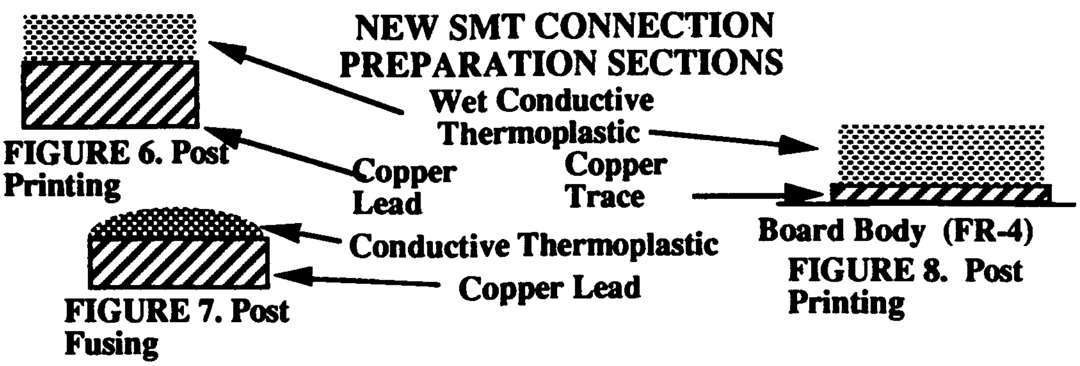

FIGURE 6. Post Printing

FIGURE 7. Post Fusing

FIGURE 8. Post Printing

The characteristics of the deposited thermoplastic can be inspected for for in-process characteristics. This will yield an inexpensive SPC check point to verify the amount, placement and initial bonding of the conductive thermoplastic.

SMT CIRCUIT CARD PREPARATION

The SMT circuit card assembly process is to screen the proper amount of conductive thermoplastic onto the circuit card assembly. See Figure 8 for a section of the thermoplastic paste deposition. Immediately following this operation the circuit card can be inspected for compliance with the desired paste characteristics.

SMT COMPONENT HOLDING

The wet conductive thermoplastic on the pads will hold the component in place during processing. Additional dot can be added to the area under the component to hold it. This will aid in relieving mechanical and thermal strains that the system will encounter during usage. See Figure 2. The limitation is that the volume of thermoplastic be limited such that there is adequate space for the thinner to escape without displacing the thermoplastic. A silk screen pattern will allow avoidance of any circuit card traces that may be in the bonding area.

The last portion of the connection to fuse will be the thermoplastic under the component. The rate of heating the component holding thermoplastic will not be a problem as long as the thermal profile requirements for the lead thermoplastic is met.

SMT COMPONENT PLACING

Place the SMT components on the circuit card. As components are placed on the circuit card the previously bonded conductive thermoplastic will come into contact with the thinner in the uncured thermoplastic, per Figure 9. This will generate wetting action between the material on the circuit card and the component leads. These connections will have mild holding force from the wetting action of the thinner.

SMT FINAL BONDING

The component leads are positioned in location as shown in Figure 9. The circuit card is moved to a curing oven where it experiences the proper thermal profile to remove the thinner and bond the conductive thermoplastic connections. When the assembly has cooled to room temperature the process of making good mechanical and electrical interconnections is complete. Figure 10 shows a section of the leads on the finished circuit card assembly.

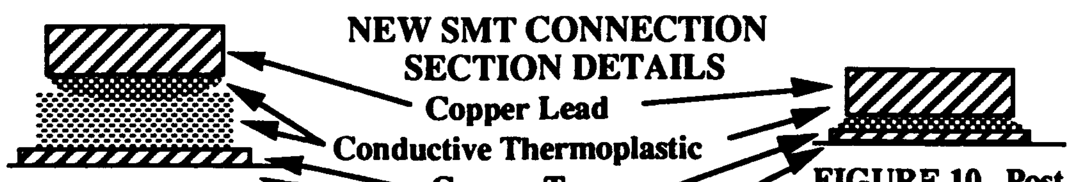

FIGURE 9. Post Assembly

FIGURE 10. Post Bonding

The detailed bonding process is as follows. The components are in place prior to heating with at least two leads in contact per Figure 9 prior to reaching melting temperature. The conductive thermoplastic will first discharge the thinner. As the temperature continues to rise it will reach the eutectic temperature. At this point it will melt, wet, and flow with the natural wetting action of the thermoplastic pulling the leads that are in contact down to a equilibrium level. This motion will generate contact and wetting of other contacts until all of the leads that meet minimum co-planarity requirements are bonded to the circuit card assembly.

MIXED TECHNOLOGY CIRCUIT CARDS

Mixed technology circuit cards will require the mixing and re-sequencing the previous process with the addition of the through hole process. One arrangement is as follows. Off line prepare the SMT components per Figures 11 12. Starting with the prepared bare circuit card, add temporary masking over those areas where SMT components will mount. Add solder plating, tinning or air leveled solder to the circuit card. Remove the temporary masking and clean the circuit card. Screen the conductive thermoplastic onto the circuit card. Mount the through hole components and wave solder the circuit card. Clean the circuit card. Dispense component holding thermoplastic. Mount the SMT devices. Fuse the conductive thermoplastic connections.

THROUGH HOLE PARTS

Use the normal through hole assembly process to install the through-hole components. Wave solder the circuit card. During this heat cycle the conductive thermoplastic will melt but will remain in place. Cool and clean the circuit card using the through hole process. The selected conductive thermoplastic material will have to be compatible with the cleaning chemicals.

SMT MIXED MOUNTING PROCESS

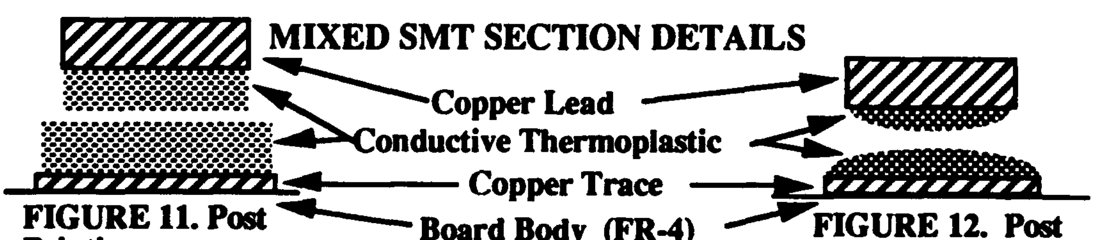

FIGURE 11. Post Printing

FIGURE 12. Post Fusing

The connection manufacturing process will consist of depositing a paste of conductive thermoplastic on each surface to be bonded. The thinner used may require some form of vapor capturing system to meet OSHA or EPA requirements. See Figure 4. for an example of the thinner recovery process. See Figure 11. for a section of the deposited unfused conductive thermoplastic. To prevent this

material from being displaced during handling it will be fused prior to use. See Figure 12 for a section of the thermoplastic after fusion has occurred for both the components and the circuit card pads.

The components and circuit cards with the fused conductive thermoplastic can now be stored and handled. The layer of conductive thermoplastic protects the conductive surfaces. The total amount of conductive thermoplastic required for each connection has been deposited.

SMT MIXED COMPONENT HOLDING

At room temperature the fused thermoplastic is smooth and non-sticky. This will require a system to hold the components during the bonding process. See Figure 13 for the configuration requirements of each lead to pad alinement. A dot dispenser can place one or more droplets of thermoplastic under each component for holding the during the assembly process. See Figure 4. for an example.

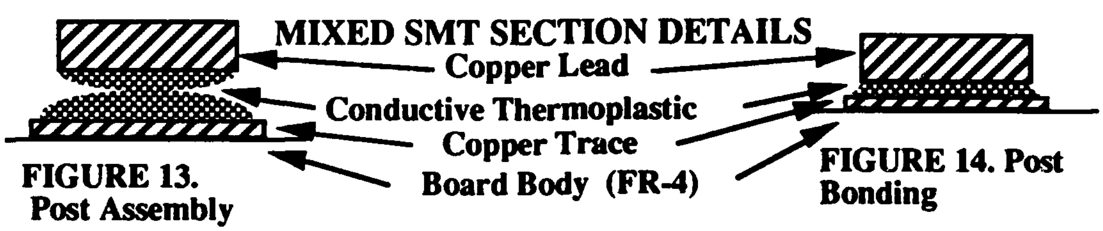

FIGURE 13. Post Assembly

FIGURE 14. Post Bonding

MIXED FINAL BONDING

The circuit card with the components in ,place is moved to an oven where the leads and components are bonded to the circuit card assembly. The processing temperature of the SMT process will not melt the solder. Figure 14 shows the final configuration for each of the SMT leads. Once the circuit card assembly has cooled it is ready for final functional test and or conformal coating as desired.

REWORK PROCESS

The rework process will use a hot air gun to melt the component

to circuit card assembly connections. The adjacent thermoplastic and solder connections will not be disturbed. The selected air gun temperature is in the vicinity of 180°C. There will be good heat transfer to the component and the leads without melting any solder connections. The hot air temperature can be increased by controlling the air flow and direction. This will allow removal of the desired component without risk to the adjacent components. The amount of conductive thermoplastic left behind will be uniform between all connections. The deforming forces applied to the component and the circuit card assembly will be minimal.

The remaining layer of conductive thermoplastic will become part of the bonding material for the new component. The new component will have a pre-bonded layer of conductive thermoplastic as previously described. However the rework processes requires a larger volume of conductive thermoplastic on the component leads.

A method to increase the volume of conductive thermoplastic on the leads is to place multiple coats of conductive thermoplastic on the component leads used for rework. This will restore the conductive thermoplastic to the original level without risk or damage. A droplet dispenser will be used to place a holding droplet of thermoplastic between the component and the circuit card assembly for process holding. The replacement component is placed using standard SMT rework tools. The bonding is accomplished using the same tools that were used to remove the original component. If the problem is a lifted lead that lead can be heated and positioned to generate a completed repair. This will not disturb the rest of the leads.

SAFETY COMPLIANCE

The metal loaded conductive thermoplastic eliminates or reduces the safety concerns relative to the soldering process. The cleanup of contaminated heavy metals is eliminated. The residues resulting from the setup and cleaning processes are eliminated. The elimination of the above materials will reduce the cost of the new process. They will also answer the concerns of the regulatory and political community. Some of these are the various Air Quality

Control Boards, EPA and OSHA.

This process will have to meet the requirements of the Underwriters Laboratories (UL), the National Fire Protection Association (NFPA) and The National Electric Code (NEC). Some of the relevant documents are UL 478 and UL 1459. The current requirement is for the equipment to meet the 90 V-0 flame rating for polymeric materials contained in the more critical locations. The conductive thermoplastic has a high thermal mass due to the metal additive. There will be no problem meeting this requirement.

These documents also require that the conductors pass the hot wire ignition test without flame ignition for 10 seconds. The interconnect system is a plastic loaded conductor. The over current test will be applicable to this application. The interconnection has significantly higher thermal mass compared to the trace. The 10 second survival requirement will not present a problem.

SYSTEM REQUIREMENTS

The process is similarity to the existing soldering process. Most of the existing SMT equipment can be used by reprogramming to a new set of process parameters. This will also be part of any adaptation to new equipment or systems resulting from any process change.

The wave solder and circuit card assembly cleaning systems are no longer required for this process. The heavy metal disposal problem is eliminated. The ionic contamination problem from the solder flux process has been eliminated. The circuit card assembly process chemistry is simplified. The reduced processing temperatures will generate a faster, safer, cheaper and more reliable manufacturing process and product. The reduced TCE mismatch within the connection will improve the intrinsic system reliability.

The SMT connection process will require a dispensing system to place conductive thermoplastic on the printed wiring circuit card assembly and components. An oven for bonding the conductive

thermoplastic to the circuit card and components will be required. As the production rate goes up and or the lead spacing goes down automatic handling equipment will be required to accomplish all of the tasks.

APPLICATION SYSTEM

The existing solder paste application systems are usable for both solder and thermoplastic applications. The preparation of the connection surfaces is a common requirement for both soldering and conductive thermoplastic systems. There is a cleanup requirement after the preparation process.

A transfer printer will be required to deposit conductive thermoplastic onto the components. This is a new equipment requirement and will replace the current tin or solder plating process for component leads. The process cost differential is minimal.

Due to the vast number of components involved some form of a robotic or transfer system will be needed to handle the components. This corresponds to the tinning and lead preparation equipment for the conventional SMT soldering process with similar cost requirements.

PARTS PLACEMENT

The last activity part is component placement. This will be no different between the current and new SMT technology. The same standard equipment that is presently in place for conventional SMT assembly will be needed. There will be no difference in the cost for this function.

BONDING SYSTEM

The IR oven requirement is for a lower temperature oven than presently used for reflow soldering. This will result in lower energy requirements. The capital and operating costs for bonding are lower.

The thinner removal process may require a vapor recovery

system if the local Air Quality Control Board dictates. This may be avoided by the selection of a nontoxic thinner system.

DEVELOPMENT REQUIREMENTS

The development project to tailor the process is beyond the scope of this article. Following is a summary of those characteristics that will have to be tailored for an optimum system with minimum cost and risk to the circuit card fabricator. The material requirements are for a particular combination of metallic powder, thermoplastic and thinner. These requirements will have to satisfy the functional electrical, thermal and mechanical requirements of the application.

The thermoplastic will form a good mechanical connection to the metallic copper and filler material in the conducting thermoplastic. The melting point of the thermoplastic should be above but close to 125°C for good operating characteristics. The melting process will be as eutectic like as practical to minimize the low temperature softening and maximize the high temperature flow. The TCE must be greater than that of the filler metal to generate good locking action between the thermoplastic and metal.

The thinner will be a selected to be safe. Future OSHA, EPA and Air Quality requirements may require a recovery system. This recovery system will also prevent contamination of the environment and the workers. The thinner needs to melt only one of the plastics in the eutectic blend. The cost of the components of the system needs to be minimized. The viscosity of the deposited material will have to be tailored for each process.

The metallic powder is copper to match the electric and mechanical characteristics of the leads and pads. The overall TCE will match the average between the lead and pad as modified by the circuit card material. The particle size of the copper will be a blend of different sizes such that each smaller size fills the voids of the next larger size. This powder will have to be inexpensive to fabricate. The particle shape will be bulky for maximum

conductivity and strength.

Tailoring of material characteristics will be required to achieve an ideal material. This will consist of those items in the metal powder, thinner, plasticizer and thermoplastic covered within the body of the text and outlined above. The purpose of this article is to develop the functional material requirements.

This is a new proposal and no Mil specifications have been developed for this process. This is a currently unapproved and undeveloped mounting process for both Mil spec and civilian products. In the civilian environment development is the only problem. The current Mil spec environment will allow any new processes if they have a verifiable advantage. The civilian market can pay for the initial p ess development. The Mil spec market can then pay for process a product testing. The alternate development process is for the gov ment to develop this process to reduce the environmental pollution.

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T.Q.M. - THE JOURNEY OF FRUSTRATION AND FULFILLMENT

by

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ABSTRACT

This paper is about the journey toward Total Quality Management in an established government contractor facility. As the title implies, this is the most frustrating and fulfilling journey a defense contractor can undertake. It addresses the problems and successes encountered while making the cultural changes that are necessary to implement the Total Quality Management philosophy. It includes actual rework, cost, efficiency, and performance to schedule data before and after the transformation to T.Q.M. Topics covered in this paper include implementation barriers, commitment to training, necessary role changes, the teamwork concept, continuous improvement philosophy, customer involvement, and the resistance to the transformation by all levels of the organization.

Numerous manufacturing facilities have attempted to implement T.Q.M. by adopting the common lip-service attitude toward T.Q.M. only to find, that without complete commitment, it is guaranteed to fail. We at Hughes Missile Systems Company, Camden Facility, are one year into the T.Q.M. journey and have been very fortunate during this period in getting the necessary worker involvement to see favorable results. This paper will share the frustrations and fulfillments experienced during the first year.

This is an actual case study of a facility that is making a successful transition to T.Q.M. It does not involve a theoretical approach but a hands-on workable game plan for the evolution necessary for the T.Q.M. philosophy to grow and mature in a manufacturing environment.

INTRODUCTION

The Hughes Missile Systems Company plant in Camden, Arkansas produces Sparrow missile guidance and control sections, as well as subassemblies for Standard Missile, Phalanx, Stinger, and RAM. The plant was struggling in early 1991. The product lines were being phased out of the factory due to rising cost and decreasing defense budgets. We had been in a layoff mode for 2 years, loosing 20-30 jobs each month. Employee morale was low even in the salaried ranks. A decision was made to adopt a new philosophy of work within our factory. Total Quality Management (T.Q.M.) was implemented. This change was envisioned as a total commitment by the management team and **not** a smoke screen complete with the normal mirrors and lights.

IMPLEMENTATION BARRIERS

The greatest hurdle is resistance to change. As we started the cultural shift that is necessary for the T.Q.M. evolution, numerous pockets of resistance formed. Everyone from the management staff to the hands-on workers exhibited reservations about either the philosophy or the implementation method. These are normal reactions by normal people. The key to defusing this is understanding. The employees have been rewarded for years for certain types of behaviors; the managers for driving to schedule and for precise decision making; the support groups for guarding their territory; and the hands-on workers for doing exactly as they are told. The only way to change these behaviors is to change the reward systems. People will exhibit behaviors that get recognized and rewarded. If you want teamwork, reward teamwork. If you want employee involvement, recognize employee involvement. If you want ____________, reward or recognize __________________. The list goes on and on. These rewards must be visible to others in the organization.

The employees must be allowed to move into this culture change at their own pace. Some accept it readily, others are skeptical. As we began to move people from their comfort zones, we learned that we had to provide support, understanding and training.

TRAINING

Our training program was very simple. Train, train, train. We designed and presented classes in:

(1) The T.Q.M. Ph losophy - 8 hours
(2) Problem Solving - 4 hours
(3) Process Improvement - 4 hours
(4) Statistical Process Control - 4 hours
(5) Teamwork - 4 hours
(6) Interpersonal Relations - 16 hours

These classes were available to all levels of the organization. They were conducted on site, during working hours, using company personnel for instruction. This 40 hours of training cost approximately $250,000. However, during this year our total training cost increased by only $95,000. Other formal training classes that were not contractually required were suspended and were addressed on the factory floor when and as they were required.

We scheduled these classes with a cross section of employees in attendance where possible. Hourly workers were trained in the same session as managers. In order for T.Q.M. to function, there must be open communications, trust, and commitment. These "mixed" classes became the vehicle for the aforementioned to develop.

Training must be supported by everyone. The easiest way to accomplish this is to provide quality training. Just as we insisted our products to be of high quality, we also insisted that our training classes be of high quality. Customer (the students) satisfaction was stressed and evaluation forms were provided for feedback from the students. Numerous changes were made to the classes using the data gathered from these questionnaires. The training in our factory has become pro-active not reactive. We provide classes as requested by the teams. Using this approach, the employees are committed to the concept. They only receive those classes that they request. This involves them in the decision loop as to what each team needs to fulfill their goals.

ROLE CHANGES

As this culture develops, the roles change for everyone in the organization. The hands-on worker becomes intimately involved in the actual management of their job. They are involved in quality improvements, schedule requirements and cost data. The task is no longer to simply perform their day to day (do as you are told) duties. They collect and chart quality, schedule, and cost data for their team. They are responsible for the overall performance of the work team. These charts are presented weekly to the General Manager in an open format between "the boss" and the team.

The supervisors' job is the most dramatically affected. The traditional job as boss, baby sitter, and policeman has been redefined into the job of teacher/coach. This change is devastating to some people. Their role is not to discipline and drive, but to support and lead. They must learn to trust the workers. Day to day process decision must be handed over to the empowered work force. Creativity must be encouraged not stifled. As the everyday supervisor tasks are turned over to the work team, they are available to direct their attention to other matters. They undertake training efforts, help with production control tasks such as schedules, work with vendors, and continuously interface with their customers. In our factory, a supervisor normally had 8-12 hands-on workers reporting to them; now our coaches have 30-50 hands-on workers to support. The remarkable thing about this change is that now the coaches have more time to spend with the teams and the individual workers because they are not handcuffed by the normal supervisor duties.

The area managers' role has also evolved from a schedule driven dictator to a people centered human being. As this change takes place, there are some casualties. Some of our managers could not make the transition and fell to the wayside. The new managers' role is the head coach. He or she provides the vision, support, budget, training, inspiration, leadership, coaching, and special attention to the teams. They really know that without the hands-on workers there are no products to market. They understand the T.Q.M. philosophy and not only "talk the talk" but also "walk the walk." These changes did not happen overnight. Numerous struggles are behind us with many more to come. Resistance at times was strong from this group and support was very weak. However, as the performance of the work team increases, support strengthens. Some still revert to their old habits when the pressure is on, but this is becoming the exception, not the rule.

The support teams had to learn "who is my customer?" Support, by the way, includes accounting, payroll, human resources, procurement, maintenance, engineering, and everyone else who doesn't build hardware. These groups formed teams to support and assist their customer -- production.

TEAMWORK

Teamwork is the key to productivity increases, and interpersonal communications is the key to teamwork. Teamwork is not stressed enough throughout our lives. We talk about teamwork in sports but then release individual statistics. Our heroes are the quarterbacks and home run sluggers, not the entire team. We as a society program this in at an early age. Our task, as a progressive management team, was to refocus our efforts on teamwork. We accomplished this by setting goals and monitoring team performance. The area work teams were given authority to make changes, responsibility for their decisions, and training to help them make the best choices. At first, this "empowerment" is dangerous; team members make selfish choices. Peer pressure is a wonderful thing. As other team members realize what is happening, they begin to take action as a team to redirect those few misguided individuals and a team emerges out of chaos.

Having to deal with personalities and attitudes can also be very difficult. These differences manifest themselves early in a team environment. During the developing states of each team, these obstacles seem insurmountable. Don't get frustrated. Success is around the corner. Management must be patient and understanding. You must listen, listen, listen to these team members. Training is essential in interpersonal relationships for each team member. We are not psychoanalyzing anyone. We are simply trying to show how and why people say and behave as they do. As the team members begin to understand some interpersonal relationships, they find that personalities and attitudes are just stumbling blocks, not pitfalls. They also learn to treat people with respect and to be sensitive to others' feelings.

As the culture changes to team efforts, productivity increases. The synergy of the group efforts toward a common goal causes this increase. The workers begin to depend upon each other to get the job done. They are not afraid to talk to each other about common problems. They stop trying to hide these problems. Fear is removed from the work place and replaced by trust. Problems are viewed as opportunities for improvement. There are no boundaries or departmental walls to hurdle; no "Chain of Command" to use. The hands-on people interface with each other across departmental lines. No

one has to bounce a decision off the "boss" when it is process related. But be careful. Empowerment is not abdication. T.Q.M. is not letting everyone "do their own thing." It is role acceptance, not role reversal. The decision making process is delegated based on the team members' skills, experience, and knowledge. Just as parents don't transfer the parenting responsibility to their children, management doesn't transfer the managing responsibility to the employees. Learning must go hand in hand with team empowerment; they must stimulate each other.

CONTINUOUS IMPROVEMENT CONCEPT

No matter what your job or position within the company, everything you do can and must be improved, reevaluated and improved again. As we perform our day to day tasks, we must work smarter not harder. We encourage employees to think about their work and regular processes as they do their routine jobs. Everyone in our organization is asked to do the following:

(1) Look for dumb stuff that you do
(2) Ask yourself "Why am I doing it?"
(3) Ask your customers "What will happen if I stop doing it?"
(4) Work within the teamwork frame to revise the process to eliminate this non-value added work.

(It is amazing how much paperwork can be eliminated by just doing this.)

We also have asked our employees to look for better methods or sequence changes that would improve quality or increase efficiency. This request has received a favorable response. Over 700 opportunities for improvement were noted the first year and changes were made to implement these ideas. This focus on improvement has a tendency to snow-ball. As one idea surfaces and the team begins to investigate solutions, other opportunities come to the surface. This phenomena happens again and again during the problem solving process. One team commented "It is hard to stay focused on the problem at hand because we are finding so many other things that need to be fixed." This is a never ending task; and the rewards are great. Not only is it good for quality and productivity, but also seeing people really work at improving their job is very fulfilling. These once quiet, sedated people (who were satisfied to just come to work, sit in their seats, and do what they were told) are excited about work. They actually smile. To come to work is not unpleasant - it's fun! This may be the greatest benefit of T.Q.M.

RESISTANCE

As stated earlier, resistance will come to those who implement T.Q.M. We found at least 5 distinctive types of opposition to the transformation.

(1) The wolf-in-sheeps clothing type - On the outside and in the public eye they support and praise T.Q.M.. However, given the chance, they will and do attack the philosophy.

(2) The Viet Cong type - These are the subversive people. They (like the one above) openly support T.Q.M.. However, these people undermine your efforts and work underground to form an almost organized resistance. Be careful, this type will hold your hand, be your friend, and slit your throat all in the same day if necessary.

(3) The I've-been-doing-T.Q.M.-for-years type - All organizations have a few of these. This is in most instances a good excuse that people use to stay in their old comfort zone. They rationalize that this is the exact way I've been operating so, therefore, I do not have to change -- result, business as usual (no improvements).

(4) The dinosaur type - these people resist and resist. They are McGregor's Theory X people. They believe that people (below them in the organization) typically are lazy, irresponsible, and show little or no ambition; therefore, close supervision, coercion, and threats are necessary to get them to do their jobs. Change comes slow to these people. They cling to the old values just as a child holds to a security blanket.

(5) The doubting type - These people will go along with the philosophy; and will patiently wait to say "I told you so" at the first sign of trouble. They are just waiting this new "program" out. They have seen other "management fads" and this is just the latest revision. After they see results, these become supporters in most cases.

These five resistors are not confined to the management levels of the organization - they are everywhere. Support groups are a hot bet of activity. These groups, having continuous interface with a fairly representative cross-section of the employees, have a tendency to spread ill will and discontent everywhere. However, if you get them to support T.Q.M., they are the ambassadors of the philosophy. Work closely with these groups and you will see a good return on your investment.

Now that you are aware of the opposition, how do you combat these forces? A lone soldier cannot win the battle. Just as one missionary to a hostile environment very often finds himself in the stew pot of the cannibals, a person unsupported in the T.Q.M. effort will surely fail. Networking is the answer. With top management's complete support, there must be someone to coordinate the efforts and a cadre of support troops. The coordinator must be at a level in the organization to influence management's behaviors and to effectively coach the staff toward the desired T.Q.M. philosophy. As the coordinator performs these duties, the aforementioned cadre develops. This is a very informal group of supporters that are from all levels of the organization. These troops are the vehicle that makes T.Q.M. function and combats the resistance. They feed information to the coordinator, spread the word (success stories), recognize the setbacks, coach their fellow workers, and help create the open atmosphere necessary for T.Q.M. to prosper. As this group (size depends upon factory size) works openly for T.Q.M., its members gradually increase. As the momentum grows, you find that almost everyone is involved. The resistance, its numbers dwindling fast, have no choice but to get on board or fall to the wayside.

An important catalyst to this process is the coordinator. This person must be totally committed to the success of T.Q.M. This must be a full time person (taken from their regular job, and not expected to do double duty). Their responsibilities include: 1) organize the training effort, 2) facilitate team meetings, 3) train and coach the management team, 4) communicate to all levels of the organization, 5) champion the T.Q.M. effort, and 6) above all, keep an eye and ear on the everyday operations of the entire facility.

FACTS AND FIGURES

Rework Percent

1990 -	20.3%
1991 -	13.9%
1992 thru August -	7.8%

Efficiency

$$\frac{\text{Standard Hours Retired}}{\text{Actual Hours Worked}} \times 100$$

1990 -	36%
1991 -	42%
1992 -	48.3%

Scrap Material Cost as a percent of Material Used in Production

1990 -	2.4%
1991 -	2.3%
1992 -	1.7%

Support Manpower (People)

1990 -	356
1991 -	218
1992 -	184

CONCLUSION

The transformation to Total Quality management is a journey not a race. Patience is a very important ingredient in the evolution. There are no exact recipes for success. Your company will probably be different than mine. Mistakes will be made, production will slow down, resistance will be strong, and you will get discouraged; however, the persistent, patient and committed will make the transition to T.Q.M. Top management support (in your facility), a commitment to training, and a genuine belief in people are essential to make T.Q.M. grow in any facility.

T.Q.M. in our factory is not a buzz word or program. It is a way of life. We still have setbacks, confrontations and resistance. Some blame T.Q.M. for every thing that goes wrong; however, the bottom line is favorable and we are improving every day. There is a sense of robustness all around, as the employees go about their jobs. I have a hard time explaining the feeling of pride that these people have about the things they are doing. Work is no longer boring. They are involved.

Total Quality Management is definitely the journey of frustration and fulfillment.

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LOW FREQUENCY ELECTRICAL BEHAVIOR OF SOLDER PASTE

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Abstract

Quantitative relationships have been established between AC electrical impedance data and physical changes occurring within solder paste, but impedance spectroscopy has yet to be employed to monitor solder paste properties during actual assembly processes. The purpose of this study was to: 1) devise a solder paste test method suitable for production monitoring, 2) extend the frequency range of the present test method, 3) develop a generic equivalent circuit representation capable of modelling the impedance properties of solder paste over the entire frequency range of the test, and 4) apply the test method and equivalent circuit to various types of solder paste.

INTRODUCTION

As electronics manufacturing comes to rely more heavily on statistical process control, new methods of monitoring process parameters will be needed. One area that requires attention is the monitoring of solder paste properties during surface mount assembly processes.

It has been shown that quantitative relationships can be established between AC electrical impedance measurements and physical changes occurring within solder paste [1-4]. However, "impedance spectroscopy" has yet to be employed to monitor solder paste properties during actual assembly processes. This work extends previous laboratory studies of solder paste using impedance spectroscopy to on-line process applications.

This study had four specific goals. The first was to devise a fast, inexpensive, quantitative solder paste test method appropriate for production monitoring applications. In-situ AC impedance measurements were envisioned as the basis for this procedure.

The second goal was to extend the frequency range of the measurements made in previous studies, which indicated the existence of valuable spectroscopic information at lower frequencies. Different equipment and procedures were required to obtain this low frequency data.

The third goal was to develop a generic equivalent circuit representation capable of modelling the impedance characteristics of solder paste over the entire frequency range of the measurements. It is through the use of this equivalent circuit that changes in the physical properties of solder paste can be derived from impedance measurements. Development of a generic circuit greatly enhances the applicability of this method.

The fourth goal was to apply the production-oriented test method and generic equivalent circuit to various types of solder paste. To support the validity of the test method and generic circuit, two different types of solder paste were studied.

In order for impedance spectroscopy to be useful in a production environment, it is necessary to develop a data base of solder paste impedance properties. This data base ultimately supports the linkage of solder paste impedance properties to changes in the physical and chemical characteristics of solder paste which occur during production.

TEST METHOD REQUIREMENTS

The long-term goal of this effort is to develop on-line process control test methods for monitoring the degradation of solder paste during assembly processes. In order to evaluate the practicality of

using a particular test method, a set of "Idealized" requirements was defined. These requirements are outlined in Table I.

TABLE I. "Idealized" Requirements for On-Line Solder Paste Monitoring Method

1. Fast and Simple:
   - set-up time < 45 sec.
   - test time < 15 sec.
   - analysis time < 30 sec.
   - clean-up time < 30 sec.
   - total time < 2 min.
2. Inexpensive:
   - solder paste used < 5g @ $.2/g < $1./sample
   - disposable sample holder < $2./sample
   - material cost < $3./sample
   - labor cost: negligible (2 min @ labor rate)
3. Quantitative:
   - provide a numeric "quality factor" for each sample
4. On-Line:
   - should reflect real-time effects of process conditions
5. Low Initial Cost:
   - instrumentation cost < $10,000

If these requirements can be met, then it should be practical to use impedance spectroscopy to check solder paste degradation at several points in the surface mount assembly process. Monitoring could be done at the solder paste printing operation, immediately prior to component placement (if substrates are queued before placement), and immediately prior to solder reflow (if assemblies are queued before reflow).

IMPEDANCE SPECTROSCOPY TEST METHOD

The first goal of this work was to devise a test method that supports the requirements of Table I. In previous studies [1-4] well-behaved quantitative time and temperature relationships describing solder paste impedance characteristics were found for a variety of conditions. This indicates that impedance spectroscopy can provide the basis for a quantitative process monitoring tool.

The proposed requirements dictate the development of a fast, simple, and inexpensive means of preparing test samples. To perform impedance measurements, a sample of material is placed between two electrodes affixed to a sample holder. For this study, two types of sample holders were used. The first of these was a disk shaped sample as is shown in Figure 1a. (Bulk measurement). The second sample holders consisted of standard FR-4 printed circuit boards with interdigitated electrode conductor patterns etched onto one surface of the boards. The electrode pattern used was that developed for the Institute for Interconnecting and Packaging Electronic Circuits (IPC) to test surface insulation resistance (SIR). (Artwork and circuit boards can be obtained from the IPC [5]). The electrode pattern is depicted in Figure 1b.

Sample holder circuit boards were prepared by a printed circuit board supplier using standard circuit board fabrication processes. The etched copper electrodes were solder plated, and no solder mask was applied to the boards.

A printing mask was created by applying electrical tape over the electrodes so as to expose a strip of conductors down the center of the electrode pattern, as shown in Figure 1b. Solder paste was spread over the exposed conductors, struck level with the surface of the tape, and the tape was removed.

This technique for preparing test samples is fast, simple, and inexpensive. Furthermore, since the sample holder is itself a printed circuit board, it can be processed along with products being assembled. Since samples are exposed to the same processing conditions as actual products, changes in the properties of the samples should accurately track changes in solder paste occurring under these conditions. These "sample holders" could even be incorporated as part of actual product circuit boards.

While the sample preparation scheme just outlined meets the requirement for a practical test method, it was necessary to determine the most appropriate electrode spacings and solder paste thickness for the test method. The IPC electrode pattern comes with three different electrode spacings: .0065", .0125", and .025". Solder paste impedance characteristics were measured using each spacing. The effects of variations in sample thickness were examined by measuring samples prepared using different numbers of layers of electrical tape (each layer being approximately 7 mils thick) as the printing mask.

Initially, the impedance spectra of various solder paste formulations were determined using bulk samples of material between disk electrodes of 1.2 cm diameter spaced .2 cm apart. Impedance characteristics of the pastes were then measured

over the range of 60 Hz to 13 MHz using a Hewlett Packard 4192A Impedance Analyzer, and from approximately .01 Hz to 10 kHz. using a PAR 5210 Lock-in Amplifier in conjunction with a PAR 273 Potentiostat. These data were then examined using lumped-parameter complex plane analysis [6]. Previous AC studies of solder paste have revealed that these systems exhibit dielectric behavior which can be represented via the equivalent circuit shown in Figure 2. Here, the conduction and polarization mechanisms within the dissimilar constituents of the paste give rise to the R_i-C_i parallel circuit combinations. The values of the various circuit elements are extracted from the raw data using complex non-linear least squares fitting techniques. A time constant, τ, characteristic of a particular constituent can be determined, where:

$$\tau = RC = (\varepsilon A/L)(\rho L/A) = \varepsilon\rho ,$$

Here, A and L represent the area and length associated with the charge transport and storage processes responsible for the observed relaxation, whereas the resistivity, ρ, and permittivity, ε, reflect the material properties.

SOLVENT-BASED FLUX SYSTEM

Figure 3 illustrates the impedance spectra found for a paste containing a solvent-based flux, when measured using the bulk sample fixture. Here, a high frequency relaxation time, denoted τ_2, is found to be 7.3 x 10^{-4} seconds. This relaxation is attributed to the flux component within the paste, and has been observed in all pastes studied to date.

Subsequently, the same solder paste was examined using circuit board sample holders with varying electrode spacings and sample thickness, and these spectra were compared with that obtained from the bulk measurement fixture. Ideally, the AC time constant associated with the flux component of the paste should be independent of sample holder configuration. However, factors such as inter-electrode capacitance, electric field fringing, and surface effects can make the measurements geometry-dependent.

Test results revealed that electrode spacings of at least .025" (the largest spacing of the IPC patterns) and print thicknesses obtained from applying two or more layers of electrical tape yield a value for the flux-derived time constant that is essentially the same as that determined from the bulk sample, per Figure 4. These data were then extended to lower frequencies, as is shown in Figures 5 and 6, where it is found that additional structure in the impedance spectra is observed.

WATER-BASED FLUX SYSTEM

Although the solder paste system discussed to this point contains a solvent-based flux, formulations containing water-based fluxes have also been evaluated. The impedance spectra found for this type of system is shown in Figures 7 through 12. It is noted that additional structure is present in the AC response of these fluxes. Here, a second R-C combination is evident at high frequencies (denoted R_2'-C_2') as is seen in the high frequency plots of Figures 8 and 10. This indicates the presence of another electrically-active constituent within the water-based fluxes.

Additional structure is also noted at low frequencies, as is observed in Figure 11 and 12. This appears to be related to phenomena occurring at the metal/flux interface. These phenomena are related to the dynamics of charge transfer, i.e. electronic to ionic, at interfacial boundaries within the sample. A circuit representing these processes is known as a Randles circuit [7], and has been included in the circuit representation given in Figure 2. The Randles circuit is often used to represent interface reactions in materials where ionic conduction is operative. It has been determined that the low frequency behavior of solder paste is better represented by the insertion of the elements, C_{dl} and R_{ct} in the equivalent circuit model of Figure 2. Additionally, the R_3-C_3 combination is included to represent diffusional redistribution of reacting species at the metallic interface.

Only modest differences were observed in the high frequency impedance spectra found for bulk and PC board water-based paste samples, per Figures 7 through 10. This is consistent with the view that these data appear to be associated with the flux component of the paste. However, significant differences were observed in the spectra seen at low frequencies for the bulk (Figure 11) and PC board (Figure 12). This suggests that charge transfer at the paste/electrode interface, rather than charge transport through the flux component, is strongly rate limiting at low frequencies in solder paste systems. If this is indeed the case, then evaluation of flux activity might be facilitated by the use of low frequency AC electrical techniques.

CONCLUSIONS

This study indicates that the evaluation of solder paste using AC impedance spectroscopy can readily be extended to sample configurations suitable for on-line process monitoring. In addition, a generic equivalent circuit model has been extended, such that the underlying physio-chemical phenomena in both solvent and water-based flux systems can be evaluated using AC measurement techniques. The AC circuit model contains elements which represent both the flux, and its reaction at the flux/metal interface. Overall, these results demonstrate that AC impedance spectroscopy can be a sensitive test method for evaluating solder paste systems in production monitoring applications.

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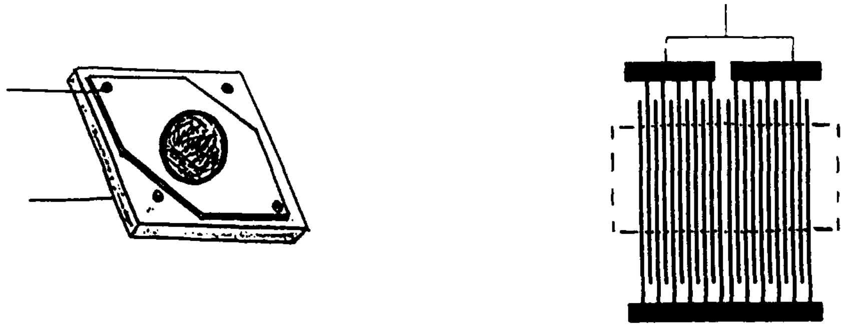

a) b)

Figure 1. Solder Paste test configurations for a) bulk measurements, and b) PC board measurements.

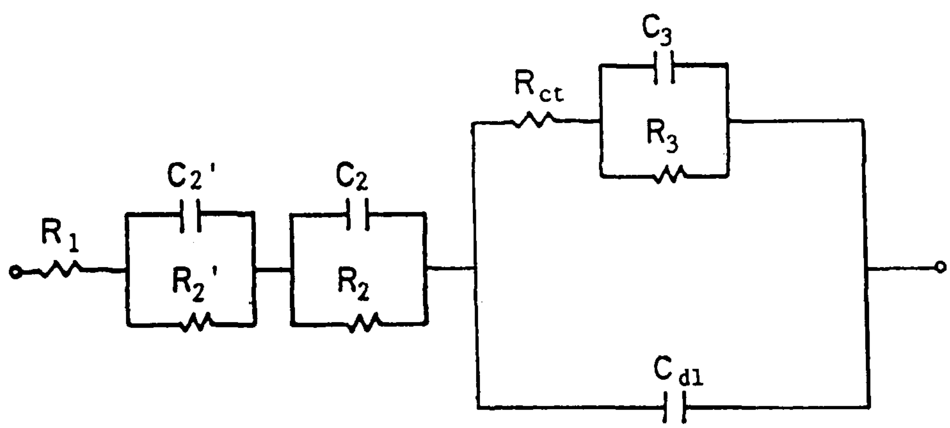

Figure 2. Generic Equivalent Circuit Representation for Solder Paste Systems.

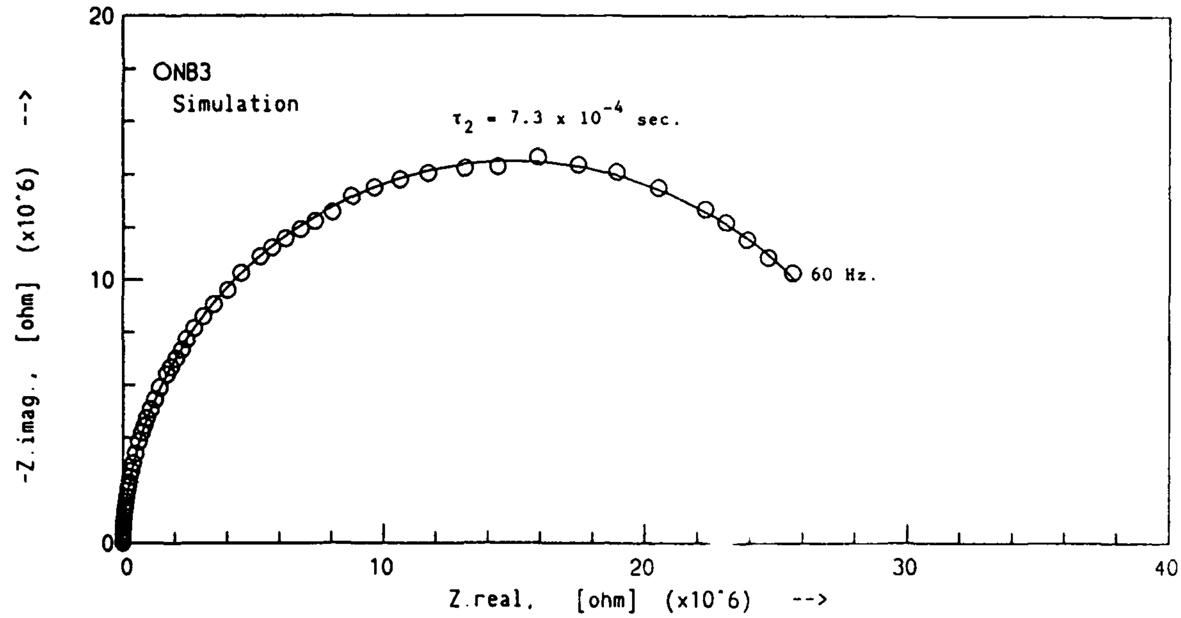

Figure 3. Impedance Spectra from 60 Hz. to 13 MHz. for solder paste with solvent-based flux (Bulk measurement).

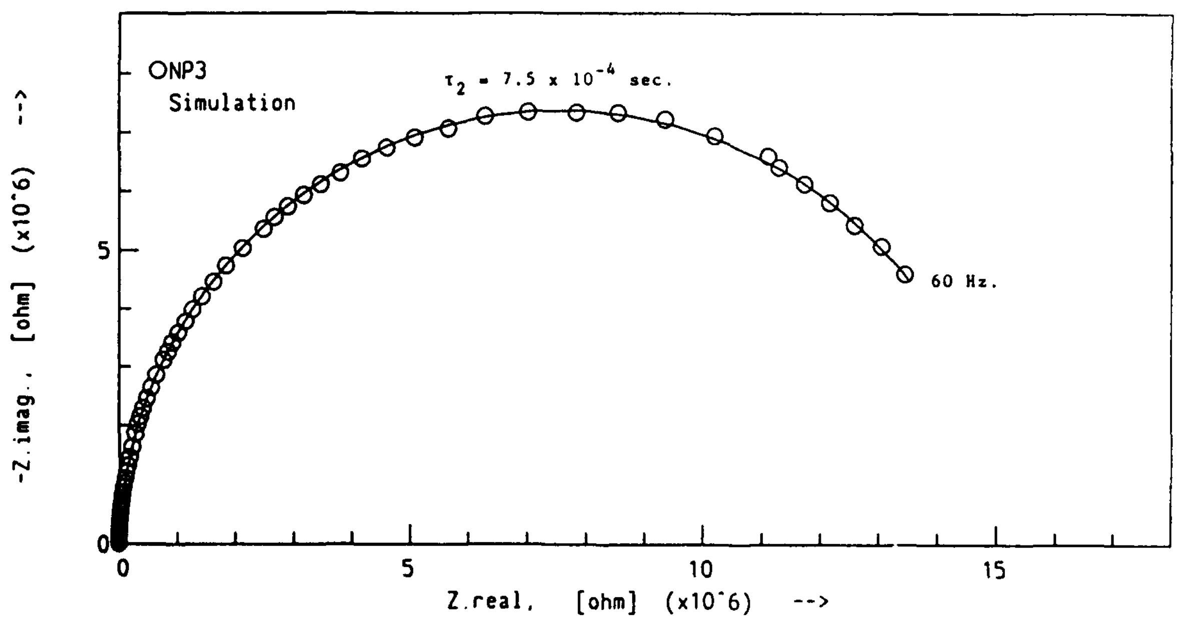

Figure 4. Impedance Spectra from 60 Hz. to 13 MHz. for solder paste with solvent-based flux (PC board measurement).

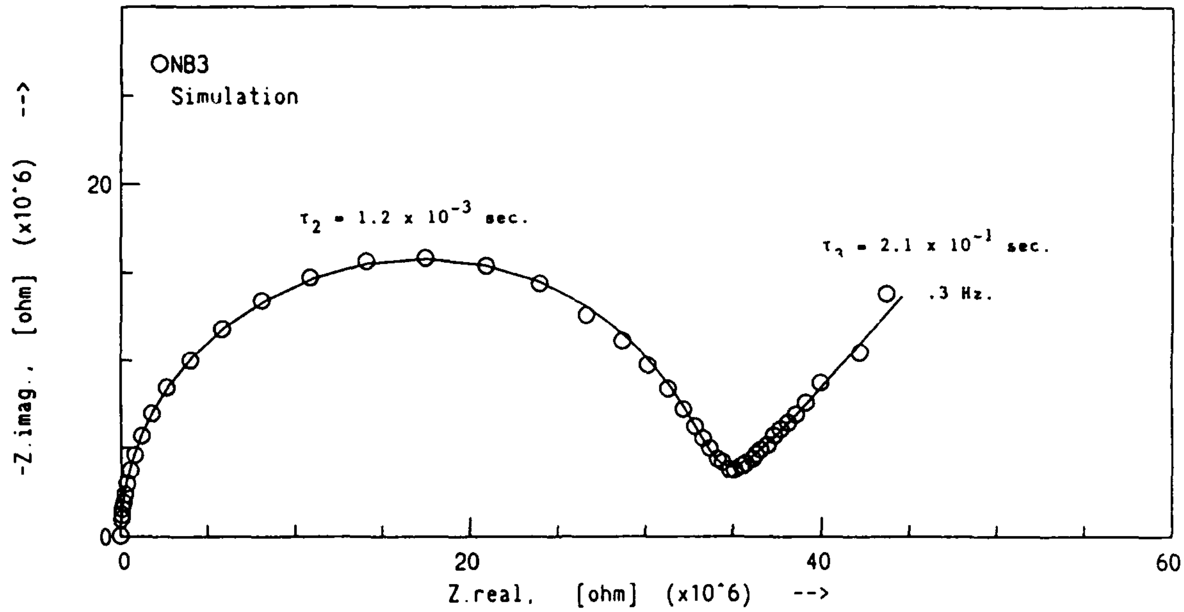

Figure 5. Impedance Spectra from .3 Hz. to 10 kHz. for solder paste with solvent-based flux (Bulk measurement).

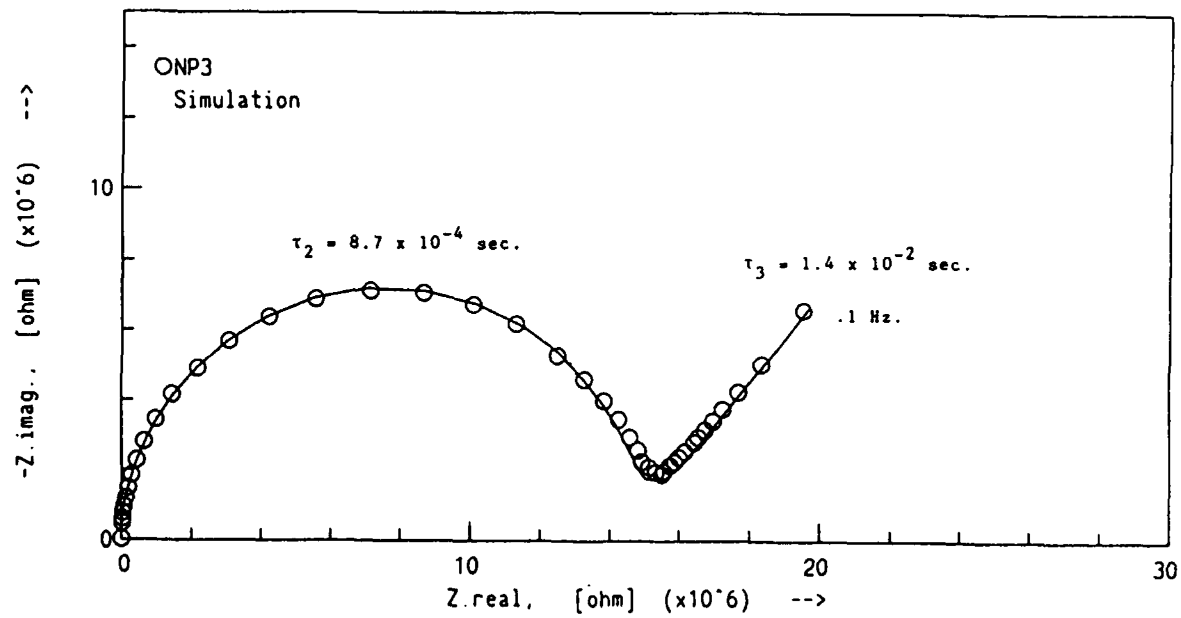

Figure 6. Impedance Spectra from .1 Hz. to 10 kHz. for solder paste with solvent-based flux (PC board measurement).

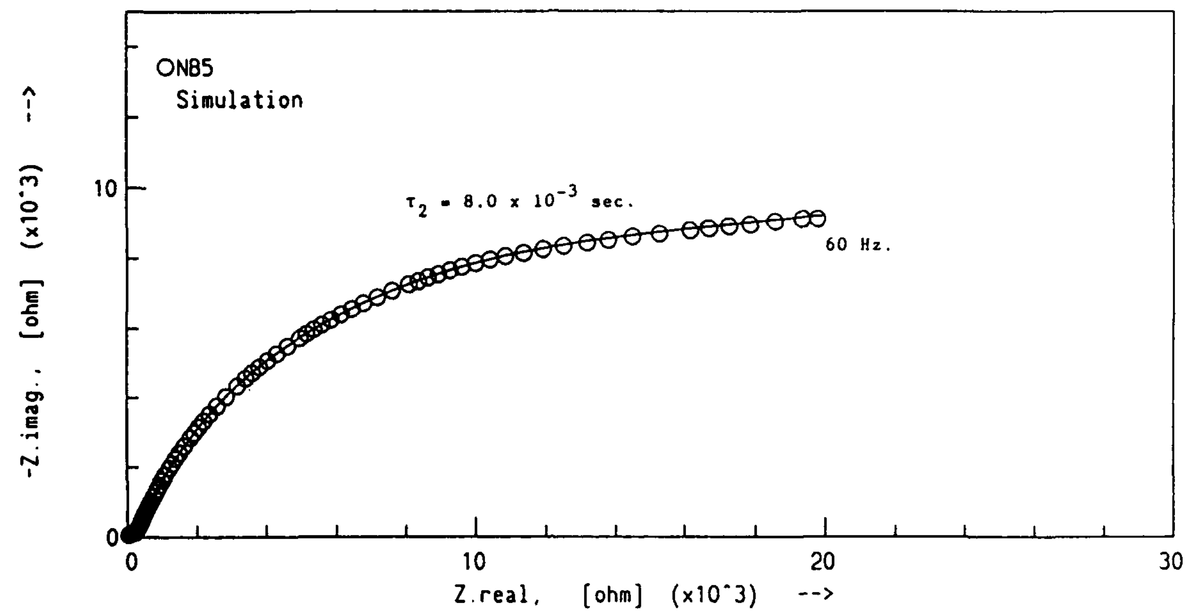

Figure 7. Impedance Spectra from 60 Hz. to 13 MHz. for solder paste with water-based flux (Bulk measurement).

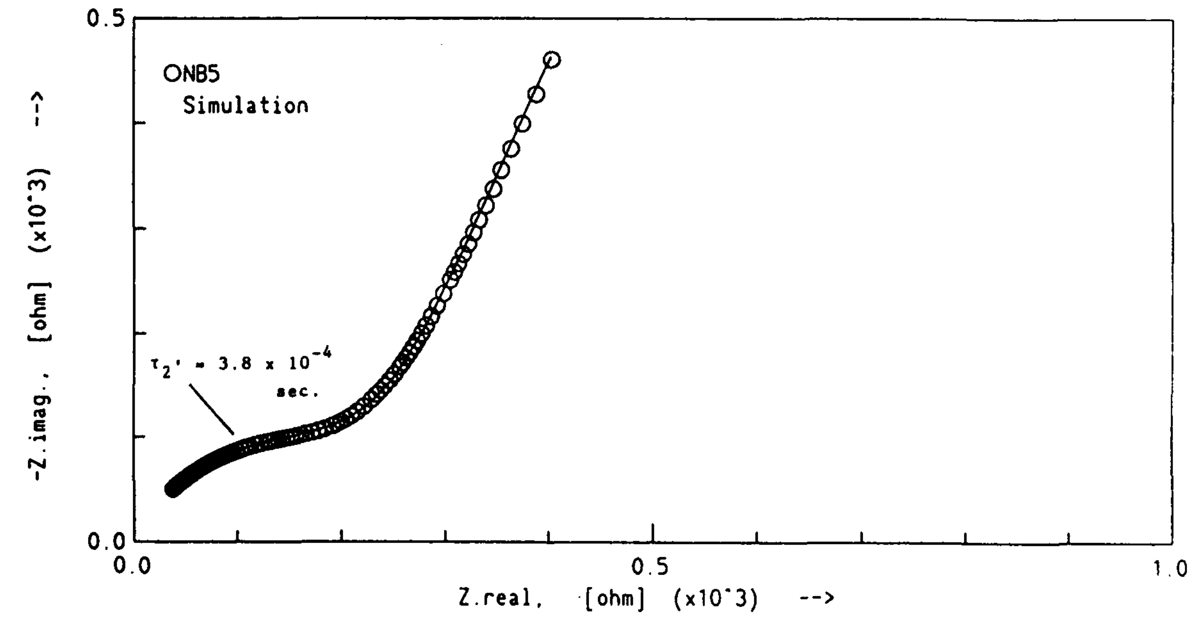

Figure 8. Expanded High Frequency/ Low Impedance region of spectra shown in Figure 7.

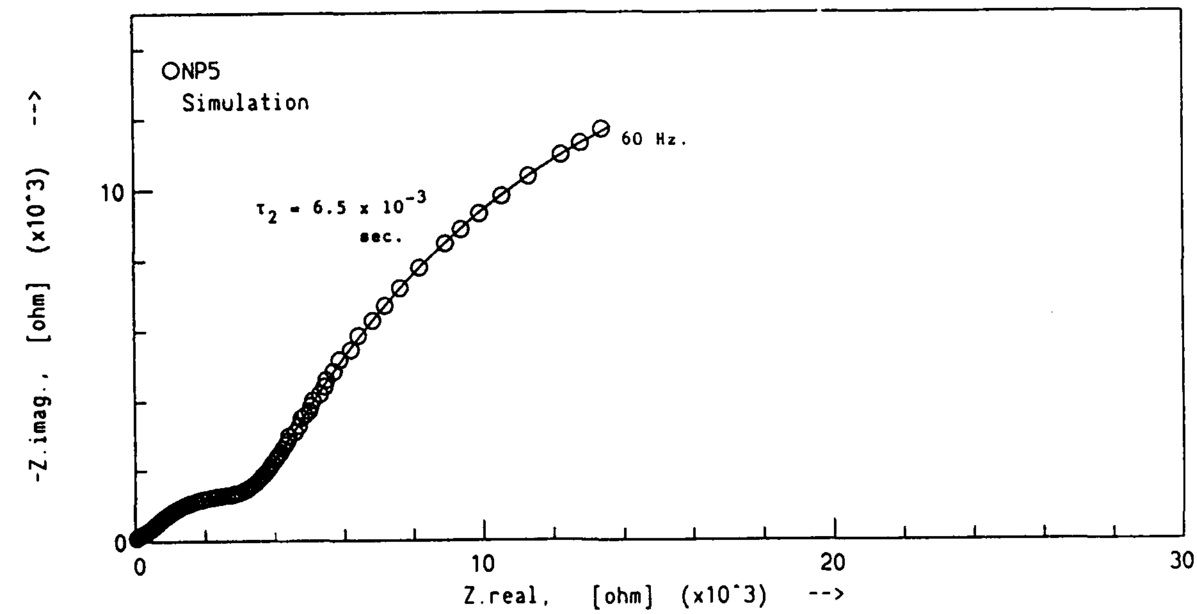

Figure 9. Impedance Spectra from 60 Hz. to 13 MHz. for solder paste with water-based flux (PC board measurement).

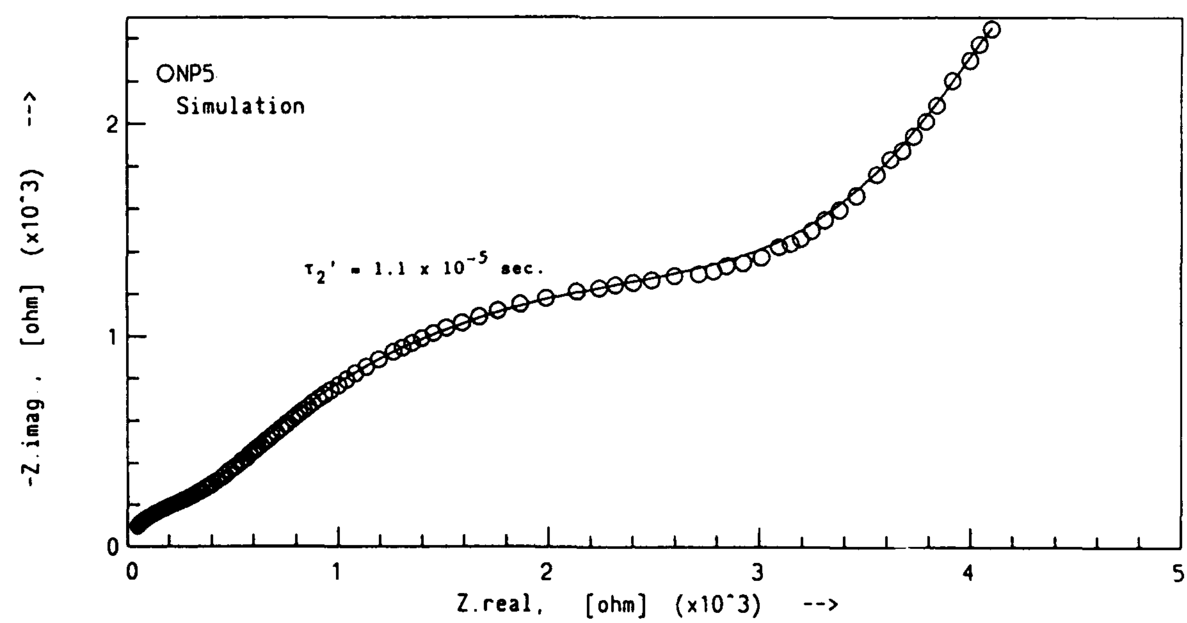

Figure 10. Expanded High Frequency/ Low Impedance region of spectra shown in Figure 9.

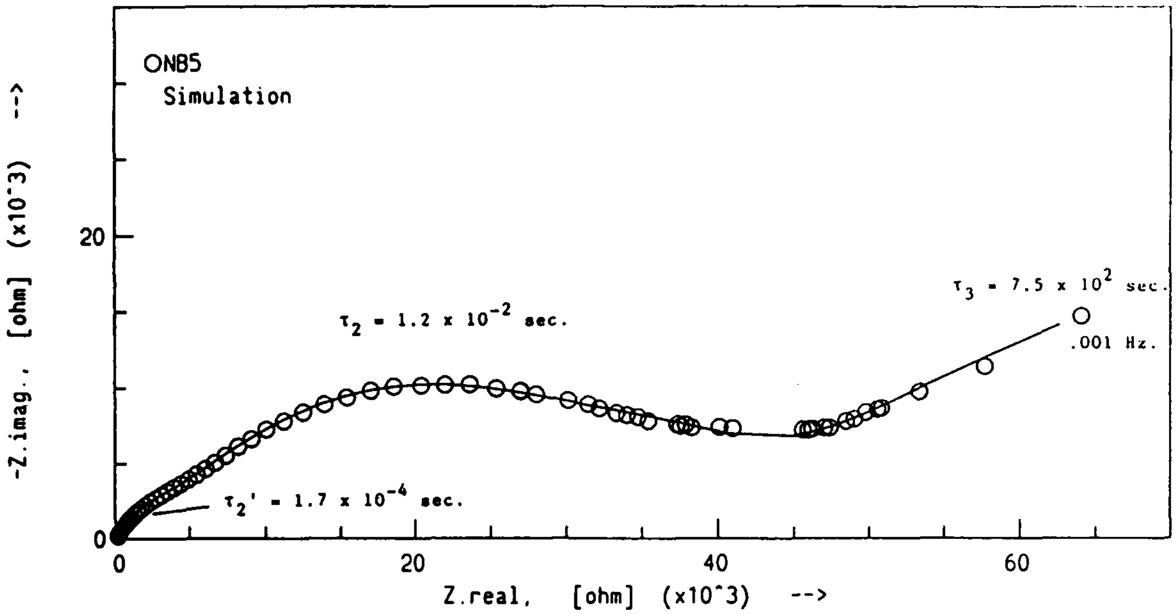

Figure 11. Impedance Spectra from .001 Hz. to 10 kHz. for solder paste with water-based flux (Bulk measurement).

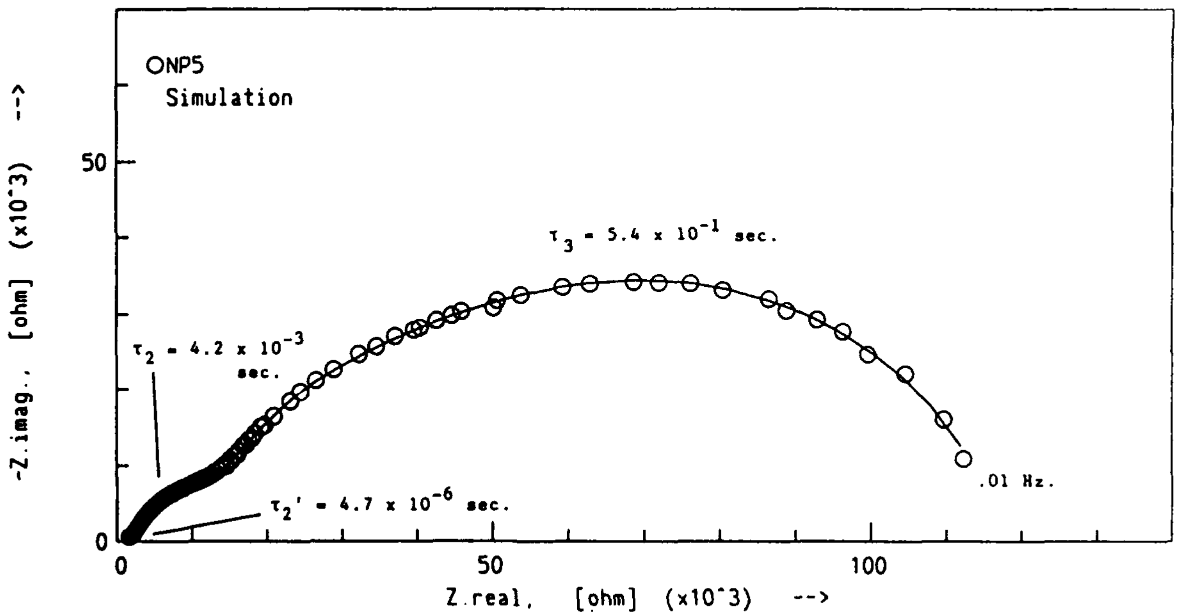

Figure 12. Impedance Spectra from .01 Hz. to 10 kHz. for solder paste with water-based flux (PC board measurement).

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HF1189

THE ENVIRONMENTALLY *GREEN* FLUX

by

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ABSTRACT

Concern about ozone depletion and the general pollution of our planet continues to gain worldwide attention. The primary offending chemicals causing ozone depletion is the use of chlorofluorocarbons (CFCs) which are widely used as a defluxing agent for rosin flux. The use of rosin fluxes generally necessitates the use of volatile organic compounds (VOCs) as the vehicle for rosin and as a rosin flux thinner. Volatile organic compounds, i.e. isopropyl alcohol, considered to be a pollutant and like CFCs, are under the control of the Air Quality Management District. Hughes dedication to find an alternative to CFCs and VOCs has resulted in the development of a water-based, water soluble soldering flux called HF1189. HF1189 is an environmentally "*green*," halide free flux comprised of citric acid, deionized water and a polyglycol free foaming agent. Hughes HF1189 flux has been used on military programs since September, 1990 with excellent results. Following implementation, there has been a complete elimination of CFCs, VOCs, vapor degreasers, rosin flux and associated waste products. Additionally, there has been a dramatic improvement in solder joint quality and conversely, a major drop in touch labor following the wave soldering operation.

This paper provides an insight into the introduction, attributes, testing and implementation of the "*environmentally green*" HF1189 flux at Hughes.

We at Hughes are gratified for the enormous support and assistance given to Hughes by the Department of Defense, the U.S. Navy, the U.S. Army, the Environmental Protection Agency, the South Coast Air Quality Management District in California and the news media. Their support have eagerly encouraged and assisted Hughes and the industry to pursue alternative ways toward a cleaner and non-polluting environment.

INTRODUCTION

One of the biggest challenges facing manufacturers of electronic systems/products is the reduction/elimination of products and chemicals that contribute to the destruction of our environment (air, land and water). Hughes, like many others in the industry, have accepted that challenge and are working diligently to save our planet from further deterioration. We the inhabitants must take pride in the continuing success stories being told by so many dedicated companies and individuals throughout the world. This paper introduces one of Hughes success stories which is entitled, "HF1189 - *The Environmentally Green Flux.*"

It is important to note that complex environmental problems can often be solved by a simple solution. One such solution lies with the invention of HF1189. The concept of the flux began in November 1989, by observing that a drop of lemon juice (citric acid) when applied to a preheated penny could promote the smooth flow and wetting of a piece of solid solder wire. This simple demonstration has resulted in the development and implementation of an environmentally green and highly efficient soldering flux.

The most important task for Hughes was to convince its customers that this simple flux could become a viable alternative to rosin flux on military programs. This was done by subjecting HF1189 to a battery of extensive chemical, metallurgical and environmental tests. Hughes has spent over one million dollars perfecting and testing this flux, and believes HF1189 is the most thoroughly tested flux in existence. As previously stated, Hughes commitment to help save the environment has made the expenditure a sound and worthwhile investment. This paper will provide an overview of validation tests, test results and methods relating to the implementation of HF1189 at Hughes.

The next step was for Hughes to interface with the custodian of the flux specification (MIL-F-14256E) to effect a specification change permitting the incorporation of a non-rosin "water soluble" flux as an option to rosin flux. This change will certainly open the door for improvements in the environment, product quality and product reliability (as discussed in this paper).

ATTRIBUTES OF HF1189

Hughes flux, HF1189 uses deionized water as a vehicle (carrier) for the citric acid activator in lieu of isopropyl alcohol or polyglycol. In addition, a "*polyglycol free*" foaming agent is likewise added to insure a stable foam head for automatic soldering. Water soluble HF1189 flux does not employ halide additives (chlorine, fluorine or bromine). Thus HF1189, consisting of citric acid and water plus a trace amount of foaming additive, is considered without question an *environmentally green flux* and has garnished a Clean Air Award from the AQMD in 1992.

Listing some of the positive attributes of HF1189 would be inappropriate without discussing its negative aspects as well. The following is a listing of positive and negative issues associated with the implementation and use of HF1189:

Attributes of HF1189

1. Not dependent on CFCs/ODCs.
2. Not dependent on VOCs.
3. Superior solder wetting performance.
4. Flux vehicle is water.
5. Flux can be removed in an aqueous system.
6. Flux is free of polyglycols and halides.
7. Eliminates AQMD tracking and disposal costs.
8. Solder joint quality is superior to rosin flux.

9. Meets surface insulation resistance per MIL-P-55110D and MIL-F-14256E.

10. Savings = $200K per year per wave solder machine.

11. Increases wave solder through - put due to increased transport speed which results in less thermal exposure to components.

12. Eliminates post solder defect screen due to superior solder joint quality.

13. Eliminates post wave solder inspection station due to superior solder joint quality.

14. *HF1189 is* *environmentally green*.

Negative Issues:

1. The flux vehicle (water) must be removed/dried prior to contact with hot solder, this will minimize potential for solder splatter. This is done by increasing air pressure to the flux air knife and by increasing the preheat temperature.

2. Use composite CCA fixtures in lieu of metal fixtures - this minimizes potential for solder splatter.

3. Mask or substitute low melt nylon inserts/spacers with thermally stable material. This will prevent a heat or thermal reaction resulting in a white coloration of inserts/spacers.

Based on the overwhelming benefits derived by using HF1189, Hughes decided to make adjustments regarding the few and correctable negative issues that surfaced. The bottom line is that Hughes did not let the few negatives hold the *environmentally green* flux hostage. As stated, the negatives can be easily corrected. As an example, the cost to switch from low melt nylon spacers/inserts to a more thermally stable material amounts to pennies in contrast to the environmental and financial benefits derived from HF1189.

VALIDATION TESTS

Before HF1189 could be considered for use in military or industrial applications, a battery of validation test plans had to be developed and implemented. However, prior to such formal testing, it was decided to perform preliminary wave soldering using HF1189. Fifty (50) circuit card assemblies (CCAs) were assembled using a variety of junk box components and circuit boards. The junk box components consisted primarily of components having failed solderability per MIL-STD-202, method 208. In addition, the components and circuit boards were not precleaned and the component leads were left long (not pre-trimmed). The CCAs were then wave soldered using a conveyor speed of eight feet per minute (rosin fluxed CCAs require a speed of four feet per minute). The soldered CCAs were then cleaned using an inline aqueous cleaner employing a 140° - 160°F. D.I. wash section and a cold D.I. spray rinse. The cleaned CCAs were examined visually using 30X magnification. The results were outstanding. The consensus of every observer was that the solder joint quality was superb. The soldering performance far exceeded expectations. Each of the 50 CCAs exhibited excellent, solder wetting on all component leads, even those components that had failed solderability testing. In addition, the soldered connections were clean, shiny, smooth and free from solder voids, peaks, bridging and shorts.

Although preliminary tests proved to be exceptional, Hughes decided that more extensive testing must be performed in order to provide the degree of confidence and reliability Hughes demands. The following is an overview of tests and evaluations performed at Hughes for such assessment.

1. Flux Activation - Reaction To Copper:

Three drops of flux per (2" x 2") copper panel from five flux types were heated for one hour at 203°F. The panels were defluxed and examined. HF1189 and RMA flux did not react. The remaining WSF types exhibited extreme aggressive reaction to copper. It was shown that HF1189 and RMA flux were halide free.

2. Flux Activation

Quality conformance "Y" test patterns per MIL-P-55110D were coated with four types of flux. The fluxed test patterns were solder floated 500°F (circuitry up) for five seconds. The fluxed specimens were conformally coated using polyurethane. Test cables were wired to each of the ten patterns. The fluxed test patterns were subjected to an environmental exposure test for 160 hours with 100 volts applied as specified in MIL-P-55110D. The following reaction was evident following removal of the 160 hour exposure:

Flux Brand	Specimens	Reaction
Brand "A" - RMA	2	No Reaction
Brand "B" - HF1189	4	No Reaction
Brand "C" - WSF	2	Severely Corroded
Brand "D" - WSF	2	Severely Corroded

It was concluded that the absence of corrosive reaction on RMA and HF1189 was due to the absence of halide and polyglycol.

3. Solder Spread Rate

A solder spread rate test was performed in accordance with MIL-F-14256D. The test concluded that the spread of HF1189 met the requirements of the noted specification.

4. Wetting Balance Test

The wetting balance (meniscograph) test comparing other fluxes with HF1189 confirmed that the wetting of HF1189 approached a theoretical perfect limit.

5. Gold Dissolution Test

Two gold, 100 pin connectors were installed on two PWBs. One PWB was fluxed and wave soldered using HF1189 and the other using RMA. The soldered PWBs were microsectioned at the gold connector pin location. Three microsections of HF1189 and three of RMA were compared for gold dissolution using a scanning electron microscope and energy - dispersive x-ray analyzer (SEM - EDXA). It was found that the dissolution of gold within the soldered plated - through holes for HF1189 was identical to RMA. It was therefore concluded that HF1189 did not interfere with proper gold dissolution.

6. Mechanical Integrity

This test was to determine if HF1189 promoted good solder wetting inside plated - through holes. MIL-SPEC, tin plated copper wires (.025" dia) were wave soldered inside plated - through holes using

HF1189 fluxed wire leads and RMA flux wire leads for comparison. The metallogragh disclosed intermetallic compound measurements identical to RMA leads. In addition, a pull to destruct test was performed on eleven each. In all cases, the wire lead broke. Metallographic examination following the tensile (pull) test disclosed no disturbance inside the plated - through holes.

7. Cleanness Validation

Cleanness te: ts were performed in accordance with specifications, WS-6536E and MIL-STD-2000 with acceptable (passing) results. Specifications require 2 megohms/cm minimum criteria. The average of three independent tests were 32 megohms/cm using IPC-B25 test coupons. Hughes Antisubmarine Warfare Systems Division has been performing production cleanliness verification testing on production circuit card assemblies since September 1990 with acceptable "First Pass" results. Using an Omegameter Model 600. Cleanness test results on highly dense, 5" x 5" CCAs disclosed an average first pass cleanness value of 1.6 µg. Na Cl/Sq. in. (0.1 low/ 5.0 high, 19 readings). Hughes maximum allowable value is 8.0 µg. Na Cl/sq. in., the maximum customer allowable is 14. It was therefore concluded that HF1189 fluxed, wave soldered and aqueous cleaned production CCAs had a cleanness value well within specification limits (with and without wash water additives).

8. Flux Entrapment Test

Eight IPC-B25 test coupons were prepared with a 3/8" wide piece of glass mounted 0.005" above and a cross the coupon circuitry. The glass laden coupons were fully immersed in HF1189 flux and wave soldered (glass side up) and aqueous cleaned using 10 ml of surfactant to forty gallons of 140° - 160°F D.I. water in the wash section, followed by a cold D.I. spray. The cleaned glass laden IPC-25 coupons were then subjected to an organic residue detection test in accordance with IPC-TM-650, methods 2.3.38 and 2.3.39. All coupons were analyzed for evidence of flux residue or converted flux compounds using a Beckman FTIR analyzer. No evidence of flux residue or converted compounds were detected.

9. Flux Absorption Test - PWB Pores

Four .062," 3" x 3" GF epoxy bare board specimens were completely immersed in HF1189 flux and an additional four specimens were fluxed using RMA. The fluxed specimens were wave soldered, cleaned (defluxed) then exposed to four cycles in an environment of 25°C to 65°C having a relative humidity of 90-98 percent. The test duration was 72 hours. A section from each specimen was microphotographed using a scanning electron microscope (SEM) at 1000X magnification for topographic (peak and valley) evaluation. It was evident that the RMA fluxed specimens exhibited a "fill-in" effect within the PWB valleys whereas the HF1189 specimens compared sharply to an received board specimen (pronounced peaks and valleys).

The next phase of the test was to soak the HF1189 specimens in a heated solution of 90 percent chloroform and 10 percent methanol. RMA specimens were soaked in a 50/50 percent solution of heated chloroform and methanol. Following the soak, each solution was analyzed using a gas chromatography - mass spectrophotomer (GCMS). GCMS evaluation detected rosin flux residue from the rosin solution and no evidence of HF1189 residue or converted compounds from the HF1189 solution.

It is concluded that HF1189 can be removed from the board surface using a standard aqueous cleaning system with or without detergents added to the wash section.

10. Surface Insulation Resistance -MIL-P-55110D.

A surface insulation resistance (SIR) test was performed on three quality conformance "Y" test patterns and three IPC-B25 (E) comb patterns. SIR testing was performed in accordance with IPC-TM-650, method 2.6.3 (specified by MIL-P-55110D). Accompanying the test specimens were four circuit card assemblies (non-polarized). Prior to environmental exposure the test specimens and CCAs were fluxed with HF1189,

wave soldered and aqueous cleaned using a surfactant, 10ml Triton X100 to 40 gal D.I. water 140°-160°F wash followed by a cold D.I. spray. The test specimens and CCA's were then conformally coated using polyurethane.

Upon completion of the 168 hour SIR test, the specimens and CCAs were found to be free of filament growth, corrosion and coating deterioration.

The insulation resistance values far exceeded the 500 megohm minimum resistance requirements. The table below shows the actual values obtained.

TABLE I. HF1189: MIL-P-55110D Environmental Test Results, Class 3
OUT OF CHAMBER

DATE	Specimen No. and Type	Oven Dried Initial SIR*	Not Oven Dried 2 Hour SIR	Oven Dried Final SIR	Status	Cleaning Method
6/90	4 "Y" 5 "Y" 6 "Y"	7TΩ 17TΩ 10TΩ	2TΩ 2TΩ 2TΩ	7TΩ 10TΩ 6TΩ	Passed Passed Passed	Cleaned using a surfactant, Triton x100, 10ml per 40 gal. deionized water, 150° - 160°F
6/90	4 B-25/E 5 B-25/E 6 B-25/E	303GΩ 1.2TΩ 114GΩ	* 36GΩ * 50GΩ * 42GΩ	* 4TΩ * 4TΩ * 5TΩ	Passed Passed Passed	

* Mean Value

MΩ = Megohms = 10^6
GΩ = Giga ohms = 10^9
TΩ = Tera ohms = 10^{12}

In conclusion, HF1189 fluxed specimens met the SIR requirements of MIL-P-55110D.

11. Surface Insulation Resistance - MIL-F-14256E

A surface insulation resistance (SIR) test was performed using IPC-B25 ("E" pattern) comb pattern coupons in accordance with IPC-TM-650, method 2.6.3.3 (specified by MIL-F-14256E). SIR values taken in the chamber at 96 and 168 hours shall be 100 megohms or greater in order to meet MIL-F-14256E requirements. Prior to SIR testing, the test coupons were fluxed with HF1189, wave soldered and aqueous cleaned using 10ml of Triton X100 surfactant to 40 gallons of 140° - 160°F D.I. water in the wash section of the aqueous cleaner. The coupons were then spray rinsed in room temp D.I. water.

Following the 168 hour exposure at 85°C and 85% R.H. (polarized), the non-conformally coated coupons were free of dendrites and corrosion.

The insulation resistance values far exceeded the 100 megohm minimum values at 96 and 168 hours "in chamber." The following table reflects the SIR values:

SIR Test Summary

Lot No.	Coupon Qty.	96 Hour	168 Hour
1	8	151 MΩ AV.	536 MΩ AV.
2	6	354 MΩ AV.	522 MΩ AV.
3	8	139 MΩ AV.	370 MΩ AV.
4	16	Chamber Failure	
5	12	197 MΩ AV.	551 MΩ AV.
6	13	Chamber Failure	

Specification MIL-F-14256E requires only three test coupons and only one test; Hughes exceeded the coupon quantity and test lots. In conclusion, HF1189 fluxed coupons/specimens met SIR requirements of MIL-F-14256E and without filament growth or corrosion.

12. Silver Chromate Test

A silver chromate test was performed in accordance with IPC-TM-650, method 2.3.33. This chloride detection test was performed as a matter of record eventhough HF1189 is chloride free. Results......"no chloride detected."

13. Halide Content Test

A halide content test was performed in accordance with IPC-TM-650, method 2.3.35. This halide detection test was performed as a matter of record eventhough HF1189 is halide free. Results......"no halides detected."

14. Materials Compatibility

A materials compatibility evaluation was performed to assess the reaction of HF1189 and other commercial water soluble fluxes to various plastics and electronic components common to CCA manufacturing. The following is a summary of the evaluation:

HF1189 appeared compatible with most of the test materials, behaving similarly to the other water-soluble fluxes. None of the fluxes proved 100% compatible with all of the materials tested: even RMA produced surface changes in some of the materials.

White deposits are not necessarily evidence of attack but are signs of surface melting and solidification in the presence of a strong acid seen on these polymers.

Other fluxes did not leave visible residues as seen for HF1189. This may be related to the noncrystalline nature (and hence transparency) of the fluxes.

Nylon 6/6 and other low melting-point insulators should be pre-wave masked or used with discretion in electronic assemblies exposed to wave soldering temperature.

15. Flux Characterization

A flux characterization test was performed in accordance with IPC-SF-818. It was determined that HF1189 was characterized as "M3C:"

M = Moderate flux activity/residue
3 = High reliability
C = Cleaning is required after soldering

16. Effluent Discharge - Waste Water

The effluent discharge such as lead, nickel, copper and tin limits vary depending on the sanitation district permits for industrial waste water discharge at individual locations. Laboratory analysis of waste water for Hughes, Surface Systems Group disclosed that, 17,470 CCAs could be cleaned of HF1189 per day without any closed-loop addition to the aqueous cleaning system.

17. Monitoring For Airborne Concentration

Active ingredient in the aqueous flux, citric acid, is a food additive. There are no methods or guidelines for sampling an aerosol of the aqueous material from an occupational health standpoint. With no sampling method available, there is no statistical relevance to any sampling conducted. Moreover, there are no published airborne concentrations for the aqueous form of this material. Any results from sampling could not be compared to any airborne concentrations published by a governing body. There is no value added in performing air sampling of the process at this time. However, to minimize exposure, all users should follow the usage and controls recommended in the Material Safety Data Sheet.

18. Thermal Decomposition Testing

A. Initial analysis was begun in the Material and Process laboratories in Hughes, Fullerton. The product was heated to soldering temperatures (500 - 600°F) to generate decomposition products, if any. No decomposition products were found. It was suspected that a fault of the experimental method was the cause of the negative results.

B. The material was submitted to the Hughes Electro-Optical and Data Systems Materials and Process laboratory for determination of decomposition products. Two samples - one with and one without color dye and odorant were evaluated for thermal decomposition products between 500 - 600°F. The laboratory found that the HF1189 proprietary material was the only outgassed product. No other material was observed to outgas from the heated flux.

19. Wave Soldering

The most difficult task to overcome when using HF1189 water base flux was to overcome solder splatter when the fluxed assemblies contact molten solder. Although the simplest thing for Hughes to do would be to replace the water vehicle with polyglycol or isopropyi alcohol (VOC), in order for HF1189 to remain an environmentally green safe and non-polluting flux, the temptation and easy-out method of reaching for IPA/polyglycol was disregarded. Hughes, like other electronics firms, feel that the continued use of harmful and polluting chemicals and soldering products must end if we are to protect our planet. Therefore, it was imperative that a work-around engineering effort be employed in order to wave solder with a flux containing a water base. The following instructions were conveyed to the wave soldering personnel:

INSTRUCTIONS FOR USING HF1189 IN WAVE/DRAG SOLDERING APPLICATIONS

Safety, Health and Environmental Precautions:

Repeated contact with bare skin should be avoided. Gloves or finger cots should be used when handling HF1189.

Equipment And Tools:

<u>Description</u>

Machine, wave/drag soldering system.
Aqueous cleaner (capable of 140° - 160°F in wash section).
Cleanliness tester (Omega meter model 600 or equivalent).
Hydrometer (capable of measuring S.G. of 1.0 to 1.2).

Material:

<u>Description</u>

HF1189 Flux.
Rubber gloves.

Procedure:

<u>Wave/Drag Soldering</u>

CAUTION: COMPONENTS/PARTS EMPLOYING LOW MELT NYLON WHICH ARE SUBJECT TO PREHEAT/SOLDERING TEMPERATURES MUST BE SUFFICIENTLY PROTECTED FROM CONTACT WITH FLUX.

Foam/Wave Application:

When using the foam fluxer, or wave fluxer, set the airknife pressure sufficiently high to remove excess flux, this will minimize solder spatter. The conveyor should be increased in order to achieve optimum quality approximately twice that used for rosin RMA. Preheat shall coincide with the conveyor speed to maintain topside board temperature in accordance with the applicable soldering specification. Circuit card assemblies, CCA's, can be placed on the conveyor fingers or with wave/drag solder fixtures/pallets. These fixtures should be non-metalic or coated with a low heat material that will minimize solder spatter. The recommended specific gravity of HF1189 is 1.15 - 1.17 and should be checked at least once a day. Additional liquid flux shall be added if the specific gravity drops below 1.15 and D.I. water shall be added if it is above 1.17.

CAUTION: DURING WAVE/DRAG SOLDERING, MAKE CERTAIN THAT THE SOLDER MODULE IS ENCLOSED OR SHIELDED TO PREVENT INJURY FROM POSSIBLE SOLDER SPATTER.

CCA Cleaning:

Following the wave/drag soldering operation the soldered circuit card assemblies should be aqueous cleaned within 30 minutes; Although 30 minutes is not critical for this flux it is desirable that aqueous cleaning be performed to establish a cleaning discipline. The aqueous cleaning system should be capable of heating the wash section to 140° - 160°F. The final rinse may be room ambient deionized spray. The

transport speed, spray pressure and water volume shall be sufficient to produce CCA's free from ionic or non-ionic residue. When aqueous cleaned properly HF1189 meets the cleanliness standard specified in MIL-STD-2000A. A non-ionic surfactant or saponifier may also be included in the wash section of the in-line aqueous cleaning system if desired.

NOTE: It is requested that after cleaning each CCA configuration/type, initially soldered and cleaning be visually examined to determine if components are sensitive to soldering, fluxing or aqueous cleaning operations.

Cleanliness Verification:

Initial Process Validation

It is requested that CCAs fluxed with HF1189 soldered and cleaned for the first time on a production basis be subject to an organic residue detection test in accordance with IPC-TM-650, methods 2.3.38 and 2.3.39. This test will validate the cleaning process.

Production Validation

It is requested that soldered CCAs be cleanliness tested using an Omegameter Model 600 tester or equivalent, this should be performed at least once per operating day. The quantity of CCA samples and cleanliness values shall be as specified in applicable contracting specifications.

Shut Down:

Flux within the fluxing module may be left in the module and covered when stored. The fluxing nozzle/chimney and foaming stone may be kept in tap water during periods of inactiveness. Contaminated/dirty flux may be discarded in accordance with local regulations.

SUMMARY

Hughes commenced wave soldering with HF1189 in September 1990 and continues to benefit from its use and also feels a sense of pride in using an *environmentally green flux*. Employees feel that through the use of HF1189 they are making, "*A world of difference.*"

Ray Turner is a Process Engineer for Hughes Aircraft Co., Inc. He has 40 years' experience in the aerospace and electronics industry with emphasis in electronic soldering.

Ray is the inventor of the "Environmentally Green" Flux HF1189. He received the AQMD Clean Air Award for the HF1189. There are two U.S. patents relevant to the HF1189 soldering flux with six more pending.

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A Reliability Assessment of No-Clean and Water Soluble Fluxes in Cable Assembly Applications

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ABSTRACT

The potential application of no-clean fluxes is of great interest in military circuit card assembly processes. The cable assembly process is another application which shows great promise for these alternative fluxes.

The EMPF and Woven Electronics investigated five different fluxes to determine the relative impact of no-clean fluxes and water soluble fluxing materials on the reliability of connector assemblies relative to current flux materials used today. The five fluxes investigated included water-soluble, no-clean, RMA, RA, and battery flux. The highly corrosive battery flux was used to establish the potential failure sites within connector assemblies. The connector assemblies were constructed using controlled manufacturing and cleaning processes. They were then exposed to 10 days of extreme heat and humidity. These environments included a constant 95% relative humidity with both a constant and cyclic temperature. Temperature cycling was incorporated to establish any potential stress corrosion phenomenon that might occur due to a corrosive flux in a humid environment. Potential stress concentration points were established on the cable assembly using finite element techniques.

By understanding the corrosion potentials, the feasibility of using no-clean and water soluble fluxes on military or high reliability connector assemblies can be established. This study investigated the corrosion generating potentials of five different flux types. In addition, the actual corrosion products and mechanisms were established along with the potential failure sites within the connector assemblies. The results of this study would be useful to manufacturers who are looking for more environmentally-safe alternatives in manufacturing connector assemblies.

INTRODUCTION

Highly reliable electronic subassemblies are a fundamental part of military hardware. As Jim reminded us at the 16th Annual Electronics Manufacturing Seminar [paraphrasing] "The men and women of our Armed Forces should never be put at risk by a poor solder joint"; by extension, no ordnance should fail to detonate at the desired time and place due to an inappropriate post assembly cleaning process. A little corrosion can be a dangerous thing.

Striving for long-term verifiable reliability can be an unreachable goal. However, the electronics industry pursues excellence by conforming to assembly standards such as WS6578 or MIL-STD-2000A. In light of the Montreal Protocol and the President's announcement that after 1995 CFC-113 and methyl chloroform will no longer be produced in the United States, the industry is finding that the accepted cleaning methods and cleanliness verification systems depended on for years will no longer work. A monumental task was confronts our industry.

The EPA/DOD/IPC Ad Hoc solvent working group has rises to the challenge. There are many who are impressed with their thorough investigation of alternative cleaning and fluxing methods. Their in-depth reports are the basis for military contractors to qualify new processes for the soldering of printed wiring assemblies (PWA). However, the array of promising fluxing and cleaning alternatives put forward by this group seem to falls short of the needs of connector and cable assemblers like Woven Electronics.

Connectors, cables and cable harness assemblies are not the same as PWAs. The PWA has made a fast-paced evolution from single-sided, sparsely populated items a mere 30 years ago, to the densely packed, multi-layer, mixed technology wonders of today. At this pace, it is reasonable to assume the evolution will continue to propagate ever smaller assemblies. At some point, an electronic signal must leave one of these miniature marvels and travel through a cable assembly to activate some remote device. Cables have adapted to the PWA evolution but are basically the same old technology. Stranded silver or tin-plated copper conductors conforming to ASTM standards take on their military identification with the application of specialized insulators and jackets. Connectors have become smaller and many are fabricated with modern amorphous thermoplastic bodies. Even older style connectors made of a thermoset filled plastic like diallyl phthalate (DAP) possess none of the latent corrosion risks of a bare FR-4 board .

Accepting that cable assemblies and PWA's are different, it may be logical to assume that their failure modes, due to a deleterious chemical such as solder flux residue, will also be different. Unlike PWAs there is little documented evidence of how cables fail. The hint of corrosion damage to jet engine cables by a citrus chemical is one of the few direct references to cable failures due to corrosion . The story of the metal shell surrounding a connector body being completely eaten away by galvanic corrosion is common in high-salt environments. If extensive cable failure studies have been done, they have not been well publicized. If the corrosion generating potential of the rosin-based fluxes were known and well-documented, the migration to a new fluxing material would be easier due to well-referenced standard.

With the absence of prior testing to use as a benchmark, the EMPF and Woven Electronics designed and implemented a test plan that would show the differences between five fluxing materials and two wire-plating types. To assure the revelation of a failure mode, a highly corrosive battery flux was used. The four fluxes scrutinized were a water soluble (cleaned with water), RMA and RA (cleaned with IPA and freon), and a no-clean flux (with no cleaning). With the exception of the samples made with the battery flux, all test joints were shining and visually clean. Although the solder joints made with battery flux were free of visible flux residues, they were gray and lacked luster.

PROBLEMS AND CONCERNS

A BRIEF DESCRIPTION OF THE PROBLEM

For a solder joint on a cable assembly to be regarded as clean, it must, at the very least, look clean. The nature of stranded wire creates an infinite number of hiding places for corrosive agents. There are critical solder joint characteristics that can be easily quantified visually. The most important attribute of a solder joint is wetting, which is readily qualified using visual inspection techniques. Cup solder joints made with well-chosen low solids, no-clean flux, sparsely applied and solid core wire solder were found to exhibit the desired shiny, smooth and concave qualities (i.e. good wetting)[3]. Even though the capability of the no-clean flux is known, little is known about its destructive potentials on cable assemblies.

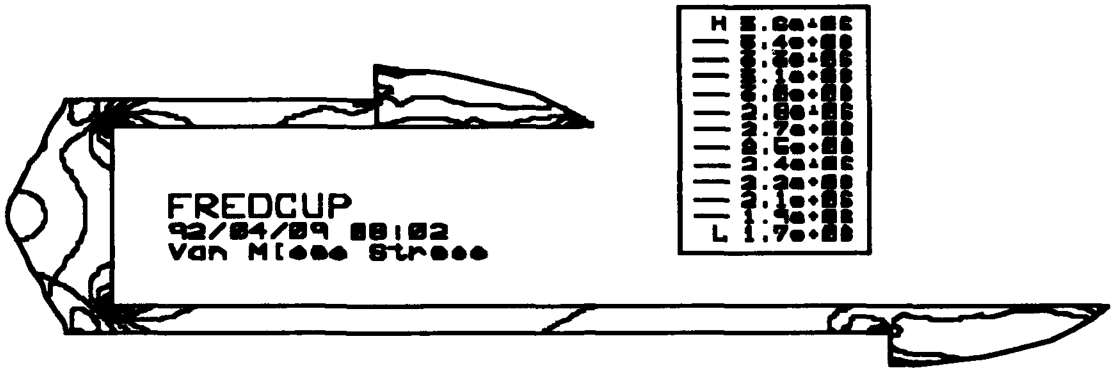

Figure 1. Finite Element Model of a Solder Cup. Stress Plot is for a Solder Cup at 80° C Static Temperature. Stress Caused by Expansion of Materials.

There are a variety of concerns in the fabrication of cables that could influence the life or reliability of the cable interconnect system. First, with the integration of an alternative flux, there are two potential sights for corrosion to occur: (1) at the wire-insulation interface; and (2) at the wire-solder-cup interface. The corrosion occurs at these locations due to active flux residues remaining after the soldering and cleaning processes. These residues establish a corrosive reaction that can be destructive to both the wire and the solder. Corrosion at the wire-insulation interface is generated from flux residues trapped under the wire insulation. The flux normally migrates or wicks under the insulation of the wire during the soldering process due to the solder wicking under the insulation. The flux, in liquid-vapor form, is in front of the molten solder as it wicks under the insulation material.

At the wire-solder-cup interface, there is a potential site for fatigue failures due to the combination of corrosion and stress, creating a stress corrosion failure mechanism. Figure 1 illustrates the stress in the solder in the wire-solder-cup interconnect system due to thermal expansion. Figure 1 shows that the areas of stress concentration are at the bottom of the cup and at the wire-solder interface. The most probable area of flux residue is at the wire-solder interface; therefore, it is a potential sight for stress corrosion if residues are not properly cleaned and removed.

The Corrosion Process

In order to better understand the corrosion capability of flux residues after exposure to heat and/or humidity, the potential electrochemical or chemical reactions must be established. These reactions will typically take place between the active chemicals in the flux and the metals in the soldered connector assembly. The constituents within flux material that are of concern in establishing these corrosion potentials can be broadly categorized into two types:

(1) Halogen-based acids reacting with the Alloy Metal(s) (Catalytic Reaction) and

(2) Ionic Conductivity of the Halogens Salts Generating a Galvanic Cell.

The halogens by nature tend to react readily with metals and form ionic compounds or salts. This characteristic can manifest itself in the reaction with the constituents, such as Pb or PbO, within the solder. In order to better understand these types of reactions, the discussion on the corrosion cycle of tin-lead solders in Manko's *Solders and Soldering* is reviewed. In Manko's book, he presents the following simplified cycle for solder corrosion:

(Metal and Air)
$Pb + 1/2O_2$

$PbO + 2HCl \dashrightarrow PbCl_2 + H_2O$

$PbCO_3 + 2HCl \leftarrow\!\!- PbCl_2 + H_2O + CO_2$
(Porous Corrosion Deposits) *(Air)*

This reaction is a classic catalytic reaction where the chlorine participates in the eventual reaction of the lead to the lead carbonate, but itself is not consumed. The lead chloride that is formed from both the lead oxide and the hydrochloric acid is characteristically unstable in the presence of carbon dioxide and moisture. The lead chloride is easily converted to the lead carbonate in this environment and at the same time regenerates the hydrochloric acid to react again with the lead oxide material. The lead carbonates are somewhat porous and do not protect the lead in the solder from acid attack; therefore, the reaction is free to continue until all of the lead is consumed. The lead carbonate on the surface of the solder appears as a white powdery residue.

In addition to the catalytic reaction that can take place between the halogen-based acids and the constituents in the solder, there is a potential for galvanic corrosion due to the conductive nature of the halogen salts. Galvanic corrosion can occur if the following two conditions are met:

(1) Two metals with dissimilar oxidation potentials are in electrical contact with each other and

(2) The two metals are exposed to a conductive solution.

In the case of the solder cup in the connector assembly, both of these conditions are met. There is a noble metal (Gold) in contact with a non-noble metal (Tin and Lead) in the presence of a conductive solution (halogen salts in the flux residue in the presence of moisture). In a humid environment or with an artificial electrical bias applied, this reaction can be accelerated.

TEST PLAN

THE PLAN GERMINATES

The goal was to establish the corrosiveness of a no-clean flux on the elements (stranded wire, solder cup and connector body) of a soldered cable interconnect. It was critical to compare the no-clean fluxes to the traditional fluxes, such as RMA and RA, in order to leverage the reliability data associated with existing cable assemblies. Since water soluble fluxes were gaining acceptability within the industry, one was added to the list. Finally, to assure that all potential corrosion sights would be revealed, a fifth highly-active inorganic acid flux was necessary. To establish consistency during assembly, all solder joints would have the flux applied externally and would use the same solid core wire solder used for all connections. Woven Electronics was already using four of the fluxing materials and the soldering techniques had been mastered.

What tests should be used? A humidity testing procedure like MIL-STD-202F, Method 103B would be adequate to revel galvanic corrosion products. In order to potentially influence stress corrosion cracking, cyclic temperatures of MIL-STD-883C, Method 1010.7 could be used.

Additional thoughts were given to subjecting the test specimens to shear loads and passing of an electrical current while under one or both of the environmental tests.

Now of what should the test specimens be comprised? The initial criteria was to use small gauge wires (28 AWG or smaller) with as many strands as possible (19 hopefully) and with a high temperature teflon insulation. After recognizing that silver-strand plating was the only option for this class of wire (and we wanted to study the more common tin-plated copper wire), we opted to do both. The wires selected were:

a. Silver-Plated, 19 strand, 20 AWG, with a teflon jacket per MIL-W-16878/6-BGB-O
b. Tin-Plated, 19 strand, 20 AWG, with a teflon jacket per MIL-W-22759/18-20-19

The connector chosen was a 104 pin rectangular, rack and panel connector fitted with solder-cup connector pins to be used with 20 AWG wire and rated to 7.5 AMPS, part #MRE 104 P, made by the Winchester Electronics Company. The test specimen fabrication was done in the spirit of MIL-STD-2000A with regards to material preparation, soldering, cleaning, assembly and packing for shipment.

Wire Preparation

1. 390 pieces of each wire type were cut to length using a Schleuniger 3750 programmable cutter. 190 pieces of each wire type that were to become part of the mating side of the test connector had one end stripped to .25" using an ITT Cannon dye blade wire stripper #CWS-100. The wires had a crimp socket contact, Winchester #100-20205, applied using a Daniels AF-8 crimp tool with a TH-4 positioner. Pull tests exceeded 20 pounds. Each crimp contact was covered with a 7/8" long shrink tube to prevent shorts.

2. 190 pieces of each wire type that were to become part of the soldered side of the test connector, were stripped and tinned. They were divided per wire type into 5 groups of 39 wires each. Each of 39 wires had one end stripped to approximately .16" using a die type mechanical hand tool - Custom Stripmaster #W/LB-0919 bladeset dipped into one of the test fluxes and tinned in molten SN63 solder at 500 degrees F +/- 10 degrees F. The tinned ends were cleaned by the following schedule and stored in Zip-Lock bags by flux and wire type.

No Clean	--->	Not cleaned
Water Soluble	--->	Water and brush
RMA	--->	IPA and brush
RA	--->	IPA and brush
Inorganic Acid	--->	Water and brush

Connector Preparation

1. 5 Winchester 104 pin connectors (one for each flux type) were split into 3 pieces with 26 pins each. The pins from the 3rd and 6th row were removed.

2. Using a band saw, the connectors were split with the empty holes used as the cut line.

3. A vibra etch tool was used to mark each set of connector pieces with the intended flux type.

4. A bench-top ultrasonic cleaner filled with freon TMS was used to clean each set of connectors before storing in Zip-Lock plastic bags.

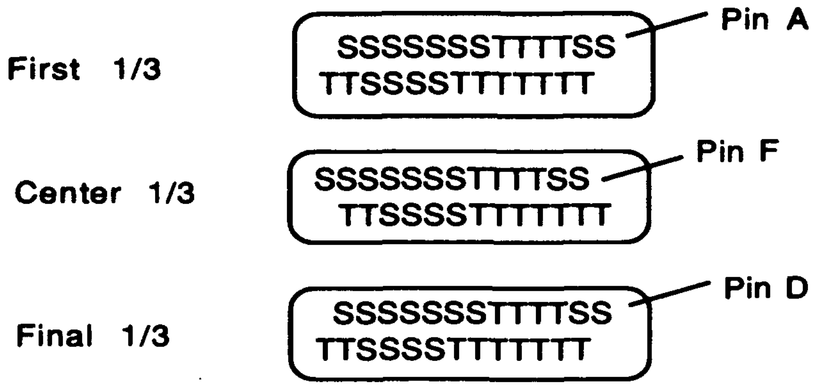

Figure 2. *Set up of the Test Specimens from the Connector.*

Soldering

Each set of 3 connector pieces had wires soldered into the cups (Figure 2) using the flux type marked. The soldering technique employed externally applied flux with solid core solder. The no-clean flux was dispensed from a modified flux bottle having a brush tip. All others were dispensed using a flux bottle with a .010" D capillary tube. The test specimen, as broken out from the original 104-pin connector, is illustrated in Figure 2 (where "T" represents tin-plated wire, and "S" refers to silver-plated wire).

Cleaning

Each 26 pin connector piece was cleaned by the following schedule, per flux type, within 30 minutes of completing the soldering operation.

Flux Type	Cleaning Process
No Clean	No cleaning required.
Water Soluble	Cleaned with brush and water after each pin was soldered. Final cleaning performed in a bench-top ultrasonic cleaner filled with warm (110 degrees - 140 degrees F) tap water. Ten minutes compressed air blow dry, then 12 hour rack dry.
RMA	Cleaned with brush and IPA after each pin was soldered. Final cleaning performed in a bench-top ultrasonic cleaning with beakers filled with freon TMS for 10 minutes, wash rack dry for 4 hours.
RA	Cleaned same as for RMA
Inorganic Acid	Cleaned same as Water Soluble flux

Assembly and Packing

At this point the 1/3 connector pieces had wires soldered to each of the cups. A socket connector pin with the same type wire as used for the solder connection was installed. Each wire had a paper label attached (with the same letter as the connector pin) approximately 6" from the wire ends. The assembly was laid out on a table, and the wires from each side of the connector were gathered together. Three tie wraps were applied to each side. Finally, the assemblies were rolled up and placed in Zip-Lock plastic bags; each bag containing three assemblies soldered with the same flux. The outside of the bags were also marked with the flux type.

Environmental Testing

EMPF classified the cables into sets based on the fluxing material used in the connector soldering process. The environmental testing on the cable assemblies fell into two categories: (1) Thermal cycling with constant humidity and (2) Constant temperature with constant humidity. The humid environment was used in an attempt to stimulate galvanic corrosion (if ionic contaminant residues were present), while the constant and cycling temperatures were used to determine if stress corrosion was a contributing failure mechanism in the connector system.

In the thermal cycling, constant humidity environment, the connector assemblies from each of the flux type categories were exposed to cyclic temperatures from 20°C - 80°C while being exposed to a relative humidity of 95%. The dwell times at both hot and cold extremes were 1 hour with a 1 hour ramp-up and a 1 hour ramp-down. The total time of exposure was 468 hours. The extended time for the cycling environment was chosen due to the desire to see if stress corrosion behavior was possible on the connector assemblies. The temperature behavior over time during the ramping operations was in a "saw-tooth wave with hold times" format. In addition to the aggressive environment, the two rows of pins on each of the connectors were exposed to 23V of static electric potential. The electric potential was applied to determine if the ionic residues would potentially excite dendritic growth across the conductors on the connector assembly.

In the constant temperature, constant humidity environment, the temperature of the humidity chamber was set at 40°C (+/-2°C) with a humidity of 95% (+0/-5%). This test fell more in line with the procedures called out in Mil-Std-202, Method 103B using Test Condition A. The total time of exposure was 288 hours. Again, an electric potential was applied across the rows of pins to potentially excite dendritic growth. It should be noted that the intent of this test was to accelerate the corrosion mechanism associated with ionic residues, not to establish the moisture absorptivity and consequential degradation of the connector material.

After the connectors were exposed to these environments, they were visually inspected for corrosion, and any potential corrosion sights were analyzed using SEM/EDAX and Auger analysis. Each of these analysis techniques was employed to determine if the residue, created during the humid environment, were ionic in nature (i.e. chlorides and bromides). The relative corrosion generating potential for each of the fluxes was established by comparing the relative peak percentage values provided by the SEM/EDAX and Auger. It should be noted that the Auger will more readily detect the lighter elements, such as Chlorine (Cl), while the EDAX is more sensitive to the heavier elements, such as Bromine (Br). The Auger looks at only a few atomic layers while the EDAX typically looks down to 3 microinches. In all cases, the two systems looked at a window that only included visible residue.

RESULTS

REVIEWING THE INITIAL OBJECTIVES

The initial objectives of the study were:

a. To determine the corrosion generating potential of each of the fluxes used in the soldering of a connector assembly. The rosin-based fluxes (RMA and RA) were investigated to determine the corrosion potential of commonly used fluxes. The inorganic acid flux was used to establish a worst-case corrosion potential that would be beneficial in establishing the likely sites for corrosion. The water soluble and no-clean fluxes were investigated to determine their viability for use in soldering connector assemblies.

b. To determine the potential failure of solder interconnects within the connector due to stress corrosion.

CORROSION POTENTIAL OF THE VARIOUS FLUX MATERIALS

RMA Flux

The connectors built with the RMA flux showed little, if any, flux residue on the surface of the wire or connector after the humidity and thermal cycling environment. The slight residue that was detected on a couple of leads was analyzed, and the results from the EDAX and the Auger are provided in Figures 3 and 4, respectively. The EDAX plot shows that there is a small Bromine peak at the lower end of the plot. From the visual appearance of the connector and wire, it appeared as though the amount of potentially active residue was not enough to generate a significant corrosive reaction in the presence of moisture and heat. Because only a few samples exhibited a residue material after the accelerated environmental exposure, there was not enough data to provide comparisons between both the constant and cyclic temperature environment. Overall, the connectors soldered with the RMA flux had the least amount of corrosion potential.

RA Flux

RA flux residue was found at the lead-insulation interface after exposure to the high heat and humidity environment. From the EDAX and Auger analysis, the residue was found to have both a Bromine and Chlorine constituent. See Figures 5 and 6 for the EDAX and Auger spectrum plots. It is theorized that the flux wicked up under the insulation during the tinning or soldering process and then became trapped after solidification. Once solidified, it is nearly impossible to clean under the insulation due to the extremely small gap between the insulation and wire and the surface tension and viscosity characteristics of traditional solvents. In addition, there appeared to be no significant difference between the connector assemblies exposed to a cyclic temperature and those exposed to a constant temperature.

Inorganic Acid Flux (Battery Flux)

From the appearance of the connector-wire interface, the Inorganic Acid flux seemed to have the highest corrosion activity. This was not surprising based on the known activity of these type of fluxes. From the EDAX and Auger plots, the relative percentage content of the halogen-based residue material is not much greater than the RA flux residues; however, the corrosion activity was much greater based on the pitted appearance of the solde . The EDAX and Auger plots for the

residue left from the Inorganic Acid flux can be found in Figures 7 and 8, respectively. There is a small peak of chlorine and a fairly large peak of bromine in the flux residue.

No Clean Flux

The No Clean flux developed a white film across the surface of the component lead with little concentration of residue at the insulation-wire interface. The residue contained very little halogen-based constituents and showed only traces of bromine from the EDAX analysis. See Figures 9 and 10 for the EDAX and Auger analysis, respectively. Again, there seemed to be little difference between the residue and corrosion products formed in a constant temperature environment versus a cyclic temperature environment.

Water Soluble Flux

The Water Soluble flux developed a significant amount of corrosion products when exposed to heat and humidity. The residue leached from under the insulation during exposure to the harsh environment and tended to concentrate near the wire-insulation interface. Figures 11 and 12 provide the EDAX and Auger analysis, respectively. From these analyses, both bromine and chlorine were found in the residue. The amount of bromine found in the residue was less than the RA and Inorganic Acid flux materials but more than the RMA or No-Clean fluxes. The chlorine peak detected by the Auger was about the same relative value as the RA flux but significantly greater than the rest of the flux types investigated.

Summary of the Corrosion Potential of the Fluxes

In all cases, there was residue remaining after exposing the connector assemblies to high heat and humidity. The RMA and the No-Clean fluxes appeared to have the least amount of halogen-based constituents (i.e. bromine and chlorine) and the least amount of active residue on the surface of the solder. In some cases, the constant temperature environment seemed to be a little more aggressive than the cyclic temperature. There was not enough data, however, to quantify these differences. The differences between the silver-plated and tin-plated materials were minimal in the corrosion process. If an aggressive residue existed, it was usually concentrated at the insulation-wire interface. It is theorized that the residue is wicked up the lead during the soldering and tinning operation and is trapped upon solidification. Once trapped, it is nearly impossible to clean due to the extremely small gap between the wire and insulation and the viscosity and surface tension characteristics of the solvent material. During the exposure to high heat and humidity, the flux material leached from under the insulation and reacted with the constituents within the solder.

This phenomenon seems almost unavoidable in most circumstances; therefore, it is critical that any residual flux residue be as benign as possible (i.e. minimal amount of potentially reactive constituents, such as the halogen-based materials). From the results of this study, it appears as though the no-clean flux materials might be best suited for connector assembly applications. There also seem to be no evidence of failures within the solder due to thermal cycling (low cycle fatigue) or stress corrosion.

A Small Disclaimer - These tests were not conducted to verify that all types of soldered connections on cable assemblies can and should be made safely with a no-clean flux or that all no-clean fluxes are equal. But only to present a body of information supporting the premise that flux systems other than RMA cleaned with CFC-113 can be used to produce a highly reliable assembly.

CONCLUSIONS AND RECOMMENDATIONS

In migrating to new flux materials in cable manufacturing, there are critical concerns that must be addressed. The corrosion failure mechanism on a cable assembly is different than that of a PWA in that the flux is trapped under the insulation in a normal soldering and/or tinning process. This trapped flux, once exposed to a moist environment, can start a corrosion process that will eventually lead to the complete destruction of the cable assembly. Therefore, when looking for a new fluxing material a benign flux (one that does not react readily with the alloy constituents or provide a mechanism for galvanic corrosion) should be sought. From this study, the two flux types that showed the least amount of corrosion potential was the RMA and the no-clean. Both the RA and water soluble fluxes actively attacked the soldered interconnects when exposed to high heat and humidity. No-clean fluxes do show promise for use in the manufacturing cable assemblies.

ACKNOWLEDGEMENTS

To all who have contributed to this work. To Jackie Wright for all her soldering skills, to John Tomczak for his suggestions and help in securing a flux sample.

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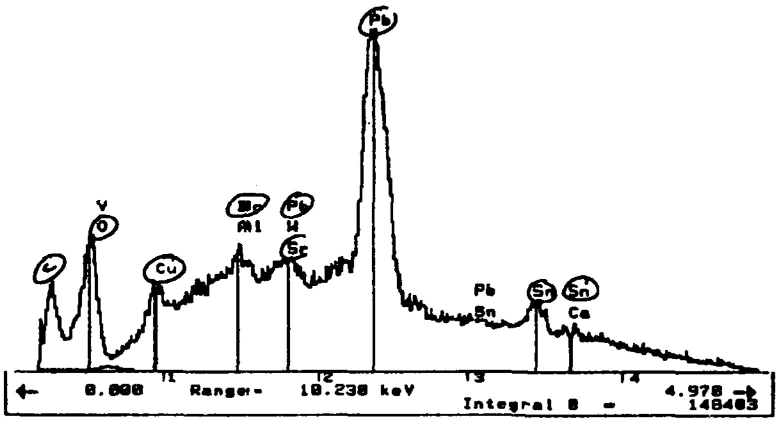

Figure 3. EDAX Plot for the RMA Residue Left on the Connector Assembly. Connector was Exposed to Cyclic Temperatures and 95% Constant Relative Humidity.

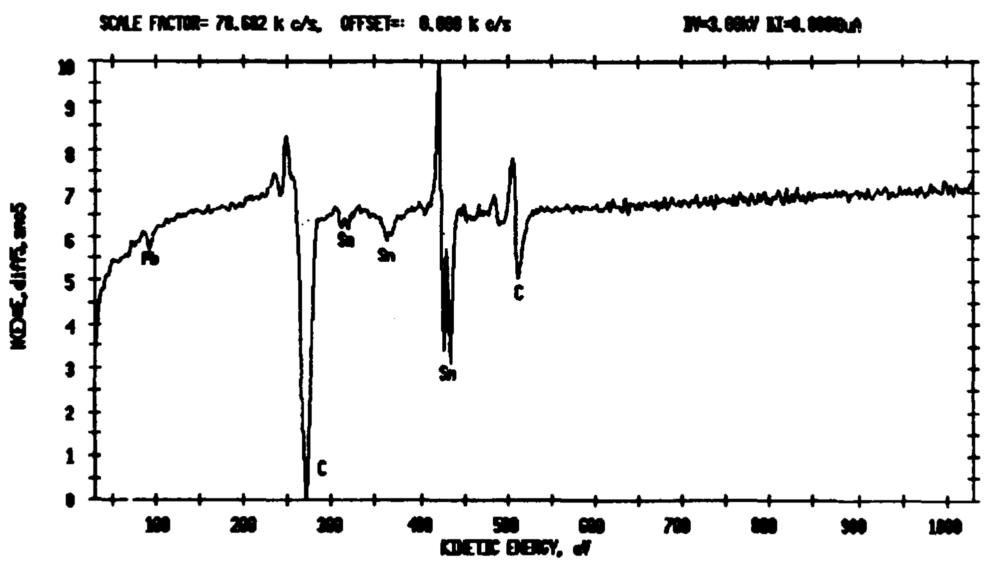

Figure 4. Auger Plot for the RMA Flux Residue Left on the Connector Assembly. Connector was Exposed to Cyclic Temperatures and 95% Constant Relative Humidity.

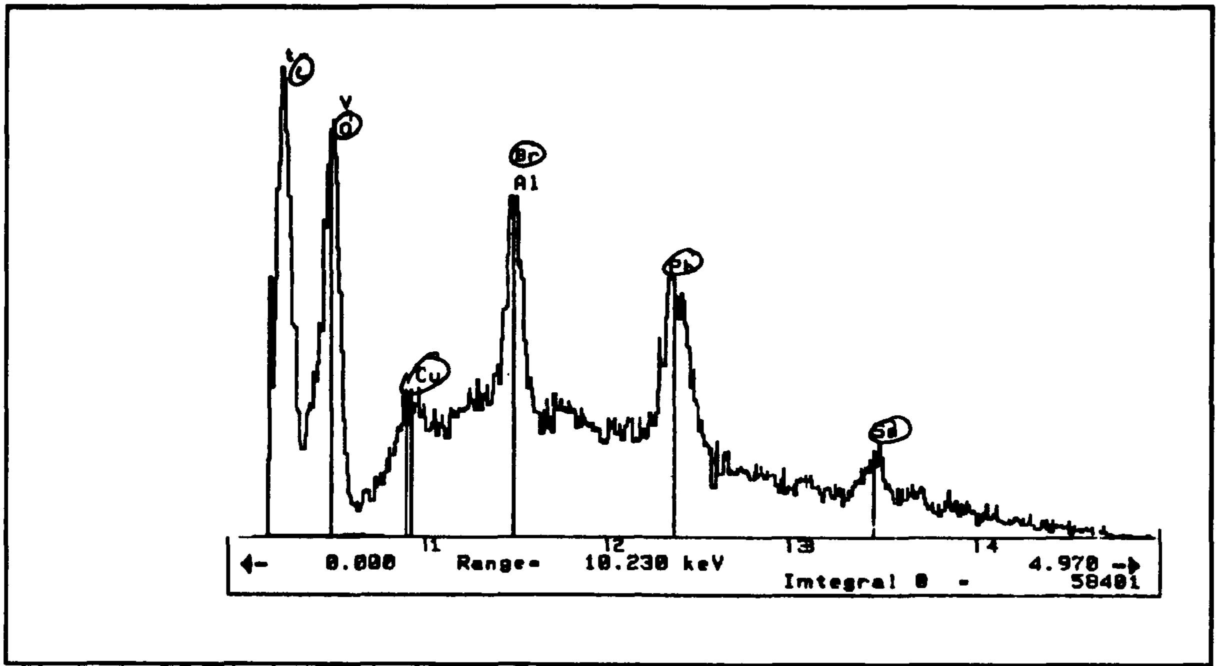

Figure 5. EDAX Plot for the RA flux Residue Left on the Connector Assemblies. Connector was Exposed to a Cyclic Temperature and a Constant 95% Relative Humidity.

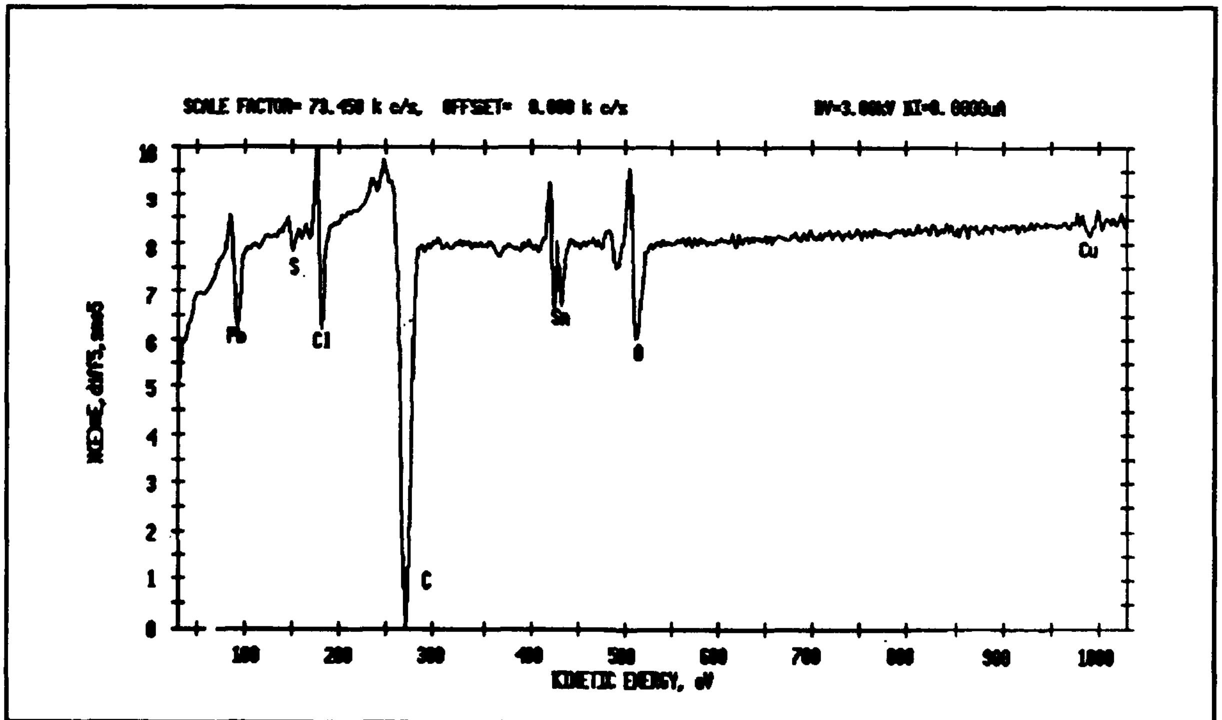

Figure 6. Auger Plot for the RA Residue Left on the Connector Assembly. Connector was Exposed to a Constant Temperature (40º C) and Constant 95% Relative Humidity.

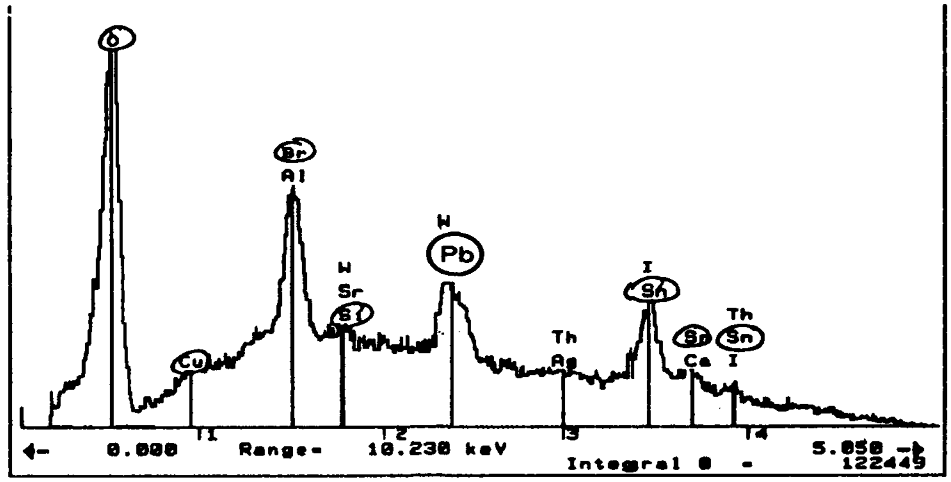

Figure 7. EDAX Plot for the Inorganic Acid Flux Left on the Connector Assembly. Connector was Exposed to Constant Temperature (40º C) and Constant 95% Relative Humidity.

Figure 8. Auger Plot for the Inogranic Flux Residue Left on the Connector Assembly. Connector was Exposed to Constant Temperature (40º C) and Constant 95% Relative Humidity.

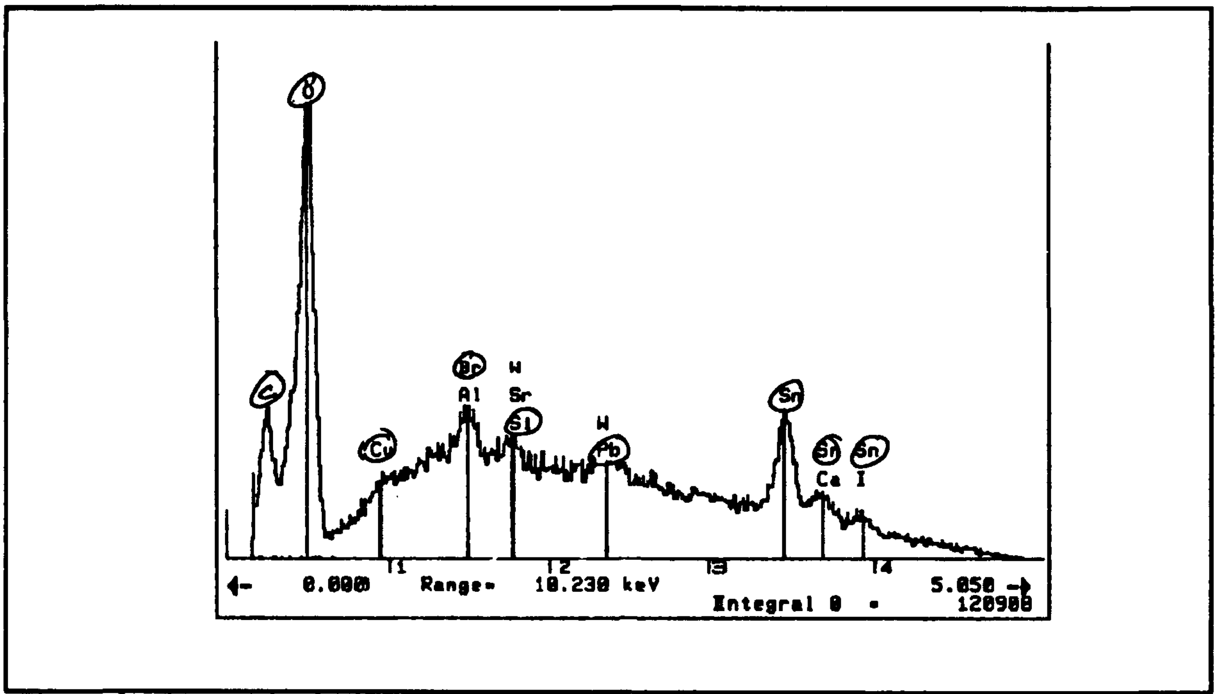

Figure 9. EDAX Plot for the No Clean Flux Residue Left on the Connector Assembly. Connector was Exposed to a Constant Temperature (40º C) and a Constant 95% Relative Humidity.

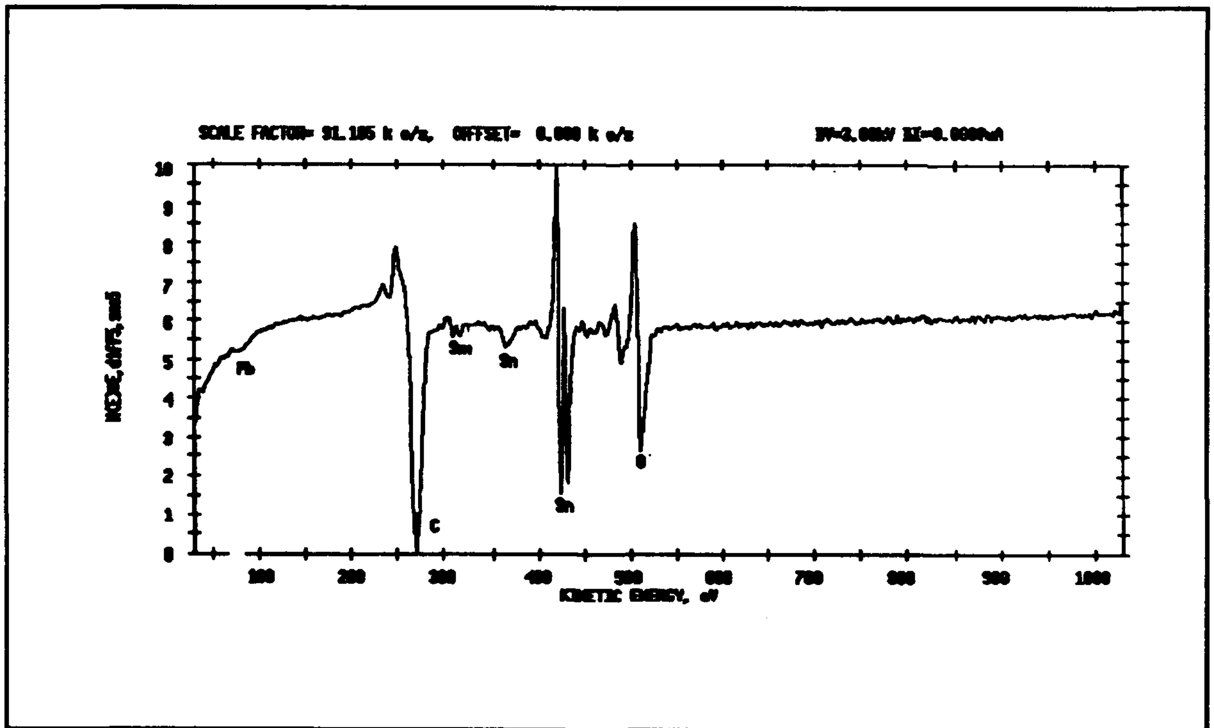

Figure 10. Auger Plot for the No Clean Flux Residue Left on the Connector Assembly. Connector was Exposed to Constant Temperature (40º C) and Constant 95% Relative Humidity.

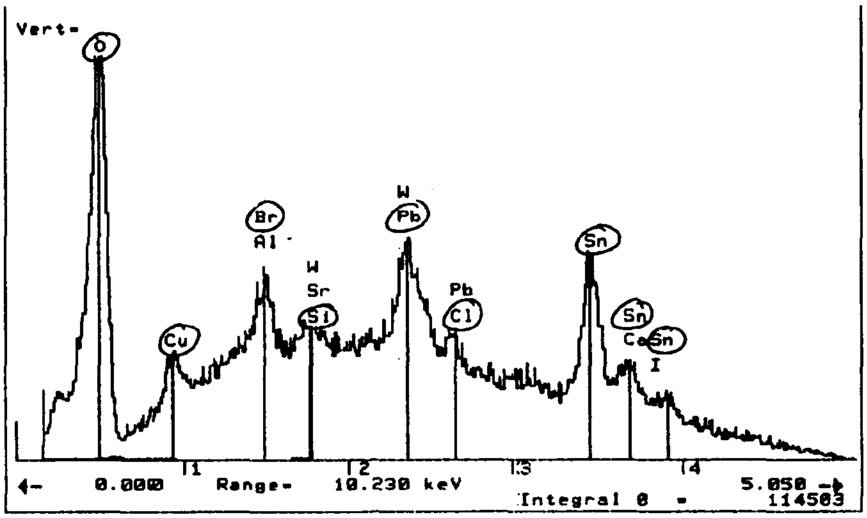

Figure 11. EDAX Plot for the Water Soluble Flux Residue on the Connector Assembly. Connector was Exposed to Constant Temperature (40º C) and Constant 95% Relative Humidity.

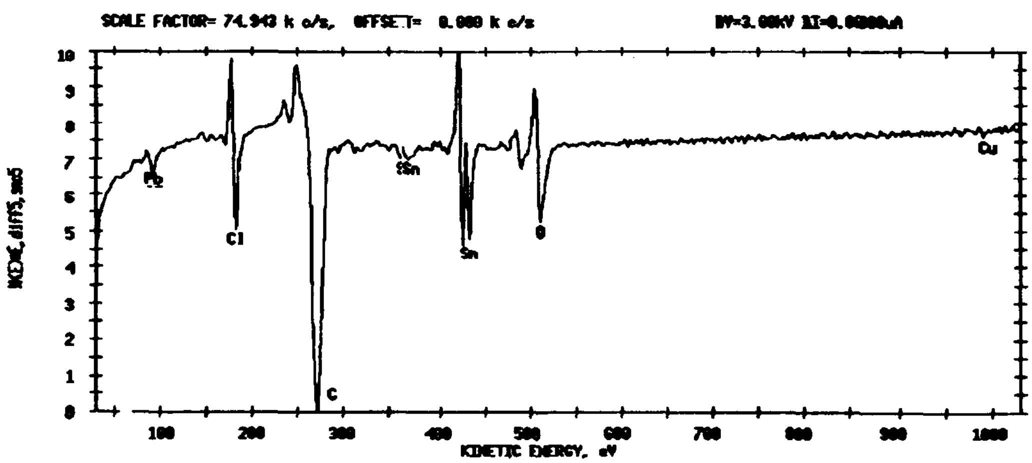

Figure 12. Auger Plot for the Water Soluble Flux Residue Left on the Connector Assembly. Connector was Exposed to a Constant Temperature (40º C) and a Constant 95% Relative Humidity.

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PROCESS CONTROL STUDIES AND CONTINUOUS IMPROVEMENT

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ABSTRACT

There exists today, a general misunderstanding of the notion of continuous improvement and an attendant lack of information regarding process control studies in terms of how, when and why.

There is no mixed meaning in the term "continuous improvement" the implication being that no process will ever outlive the need or opportunity for improvement.

Continuous improvement does not necessarily imply that a leveL of improvement must be attained each week, month or year. After having made the obvious improvements and studied the less obvious, one will normally reach the next plateau. That is, costs of further improvement exceed the return on investment; and the inability to progress due to the lack of technology. One does not simply abandon the process improvement effort at this point, rather suspends and monitors the program subject to periodic review. When an opportunity is presented or a technology breakthrough occurs which makes further improvement possible and econom- ically feasible, the program is reactivated.

Process control studies typically start with inspection capability studies for both attributes and variables as they apply to the process. Why inspection capability? There is no better test of performance and appearance criteria, for one, and no better way to determine if the inspection system and inspectors are helping or hurting the process.

Essentially, engineering is responsible for establishing functional and appearance criteria which is then, by plan interpreted and enforced by quality control. Too often, criteria are incomplete, vague, or immeasurable and lacking viable definition of conformance and quality control "invents" or modifies criteria. The same studies used for inspection capability may also be used to evaluate both mechanical and electrical performance test situations and will again, evaluate the design and process. Methods such as this with control charts for documenting the original state and tracking subsequent actions are important ele- ments in any process improvement effort.

CONTINUOUS PROCESS IMPROVEMENT

What exactly is continuous improvement? Continuous improvement is not new and not radically different from what has historically been done in developing products from prototype to maturity.

Conventionally, product and process improvement result from a series of unorganized engineering change requests. These change requests are often a response to serious production or fabrication issues, or customer complaints. They are too often answered with insufficient insight and thus fall short of the most effective solution.

Most product and process improvement efforts are driven by and aimed at the solution of pressing problems. Once done, little or no action follows.

The other major driving force is that of interface and appearance enhancement. We see much of this in the automobile industry in subtle to pervasive changes in design and features from one model year to the next. However this does not mean that the nagging problems are receiving the attention they deserve or would receive in an organized improvement program. Many problems continue year after year virtually unrealized and unchecked.

We often miss the opportunity to totally refine design parameters for optimum assembly and the opportunity to further develop the process in many ways. Among these are: standardization of practices; verification of the process; certification of operators; reduction or removal of inspection points and observables.

Continuous improvement implies a programmed approach to product and process maturity consisting of several well defined stages.

Concurrent design - Typically there has been some level of interactivity between design engineering and support engineering owing largely to the need to develop tooling and test facilities in advance of a release. However the effort is generally driven by design engineering and there is little doubt over who is in charge.

Concurrent design as a concept, involves design and support engineering, quality control and assurance, and the designated production department early in the design. The team members have an equal voice in design and assembly considerations. The synergistic efforts of the team result in a more highly refined and capable assembly at the time of release.

Design verification - Again, engineering has typically

performed a series of test on new products to assess durability, reliability, and utility. When applied to a multidiscipline group, the process of verification adds statistical studies, tolerance analysis, and fault tree analysis to the process. The goal is to insure that the product actually performs to the definition and specification, with margin and that all weaknesses and potentially troublesome design features have been resolved or understood.

Process verification - It is vitally important that the product be more than simply manufacturable. It must be efficiently manufacturable. That is, the product must be of such a design to preclude assembly errors, assembly is simple and systematic, well documented, and the successful build is readily distinguished from the faulty. Documentation, such as engineering functional specification and parametric criteria are implemented by the assembly instruction and inspection instructions are consistent with those requirements. All required tools and facilities are in place or planned.

Post release refinements - Despite all the preplanning and testing, there will always be design and process flaws or options which on one hand hinder production and on the other prevent maximum efficiency. The same team is still needed, some to a lesser extent than others but all must be accessible and committed to the process for essentially the product life cycle. Replacements must be provided as attrition erodes the original team.

Continuous improvement - Having done all the "right things" in bringing the product into production and enhancing the design or assembly process, does not bring an end to the effort. A slowing of activity is normal and expected but, a number of opportunities will have been identified. For lack of viable alternatives, technological capability, or capital budget they will remain unimplemented. Also, time will reveal other opportunities which were unforeseen during the verification stages and initial production. Customer input will often result in an improvement, modification, or enhancement. Although there is still room for a "mature product", it does not follow that a design freeze and discontinuation of sustaining engineering support is appropriate. We must think in terms of being willing to continue improving the design and process throughout the product life.

Does this mean we can never expect to disband the team and allow the members to get on with a new project?

Team activity after the verification series is usually an occasional meeting which may be called periodically or when an improvement opportunity is presented. The team involve- ment is generally no more disruptive than the handling of an

engineering change request. The fact is, the change request will normally involve essentially the same people comprising the team. The difference is, the people who would otherwise review a change notice or order reflecting an engineering decision are now a part of the decision making process.

Who decides when, what, and how often to improve a product or process?

The who is essentially any team member and anyone connected with the product who recognizes an opportunity to improve any part of the process. This recognition may be received in the form of a problem statement for which an answer is not available, or the statement of a problem and a proposed answer. The teams most important function is that of keeping the lines of communication open and responding promptly to issues.

The element of when is better answered with another question. When do we now generate a change request or change the process or equipment? Obviously these things are done when there is a problem with the process or design or a change is revealed that will enhance the process or prod- uct. It is not uncommon for no additional improvement to take place for a year or more. Some improvements have been known since the early stages of development and deferred for lack of technology, budget, or return on investment. These must be reviewed periodically and re-validated. With rapid technological advances, that which was not feasible last year becomes a distinct advantage this year.

What to change is no different. The process should be periodically reviewed particularly with the assemblers, testers, and inspectors in order to better understand what works and what doesn't. The changes that can be made within the existing budget and organizational capability should go forward immediately. However, no change should be made that doesn't result in a tangible benefit. That is: lower production or materials cost; ease and surety of assembly, test, or inspection; or reduction or elimination of non-value added elements.

How often changes should be made is easily answered. As often as the opportunity arises and all the qualifiers are met. Changes need not occur at regular intervals to demon- strate continuous improvement. Having the program in place and a standing team connotes a state of continuous improve- ment.

Who makes the rules for continuous improvement? You, the manufacturer makes the rules for continuous improvement. You alone have the information necessary for making a business decision involving up-front dollars and pay back. This doesn't mean you should take the easy way out and simply say "I have

no money for capital expense, so that's the end of it".

At the extremes, we have manufacturers "controlling costs" by not fixing what isn't broken, and quality organizations and consumer advocates insisting on unbridled continuous improvement. Neither position is realistic. There must be balance between improvement and resource. A business can just as easily approach chapter 11 through either extreme.

Ironically, the series of military and defence department standards and specifications have advocated continuous improvement. Perhaps, the message was subtle and many contractors mis-understood the intent, but it is there and has been for decades.

Take for example, Mil-Std-2000. The standard is structured such that rework is to be performed only after inspection. This allows for data collection and an opportunity to correct the process element producing nonconformities. Additionally, defect codes are separated into A and B categories. The later are termed process indicators and do not require rework. The implication is clear and so is the requirement for continuous improvement.

In retrospect, we see manufacturing in the 70s and 80s in a "buyer beware" business posture. In order to increase profits many companies went off shore and the quality of goods suffered. However, as quality programs began to drive foreign industry and continuous process improvement became a reality, U.S. companies began to lose market share in major proportion and were threatened with extinction. We see a resurgence in U.S. manufacturing today because there is no other way to compete and possibly because of a realization that the need to satisfy the customer must be the ultimate driving force in product and process improvement.

Having no plan for continuous process improvement can be taken to mean that a company is simply unresponsive to the customer's needs and desires. The forward looking company anticipates the customer's needs, others react.

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SOLDER GRAIN STRUCTURE IMPLICATIONS FOR HIGH-RELIABILITY SURFACE MOUNT ATTACHMENT

by

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ABSTRACT

A preliminary study was conducted to measure internal voids and the grain structure of solder joints formed by different soldering processes using tin-lead eutectic solder. Seven methods were analyzed within two categories of soldering processes: five methods of hand soldering and two methods of vapor phase soldering. The hand soldering methods included hand soldering with cored solder wire, hand soldering with and without solder paste cure, and reflow hand soldering of pre-tinned components and substrate with and without flux. The vapor phase soldering methods included soldering with and without solder paste cure. Cross sectioning of these joints revealed that curing of the solder paste reduces the number and size of the voids. In addition, the reflow hand soldering process using pre-tinned components and substrate yielded the lowest incidence of voids. Additional flux did not affect these results. The grain structure of the pre-tinned reflowed joints was similar to that of the vapor phase soldering process with paste cure and had lead-rich regions of 1.80 to 2.56 sq. μm.

INTRODUCTION

A study was conducted to determine the effects of voids and grain structure on a tin-lead eutectic solder joint. Voids are a problem associated with the use of solder pastes (Reference 1). The size and distribution of the voids were studied since reports have indicated that large voids may degrade the electrical, thermal, or mechanical properties of the joint(Reference 2). The ultimate goal of the study is to determine if it is possible to correlate void and grain structure with the fatigue life, and therefore the reliability, of the solder joint.

Other investigators who have examined the effects of grain structure on the reliability of a solder joint found that the rate of solidification determines the grain structure of a solder joint (References 3 and 4). Faster cooling produced finer grain structures, which improved the solder's fatigue life when tested. Mei and Morris tested three different cooling rates on 60Sn/40Pb solder joints and found that the isothermal fatigue life of quench solidified joints was twice that of furnace cooled joints (Reference 3). Wild published similar findings from mechanical fatigue testing of leadless ceramic carriers that had been assembled using hand soldering, vapor phase reflow soldering, and vapor phase reflow soldering with rapid cooling. The data showed that faster cooling rates in solder improve the

fatigue life of the solder joint (Reference 4). Thus, I anticipated that hand soldered assemblies would have finer grain structures, which would yield longer fatigue lives than vapor phase soldered assemblies.

This paper contains the details of a background study of seven soldering methods. The purpose of the study was to quantify the effects of different soldering reflow methods on the grain structure and porosity characteristics of a solder joint. The results from this study were used to select four soldering methods for thermal cycling tests.

EXPERIMENTAL PROCEDURE

In order to gain an understanding of the grain and void phenomena, a variety of soldering methods were analyzed:

1. Hand soldering process
   a. Hand soldering with cored solder wire
   b. Hand soldering without solder paste cure
   c. Hand soldering with solder paste cure
   d. Pre-tinned components and substrate, reflow hand soldering using liquid RMA flux
   e. Pre-tinned components and substrate, reflow hand soldering without flux

2. Vapor phase soldering process
   a Vapor phase soldering without solder paste cure
   b. Vapor phase soldering with solder paste cure

Hand soldering was performed with a solder iron set at 316°C. For the hand soldering process with solder paste the cure schedule was 30 minutes at 105°C. The cure schedule prior to vapor phase soldering was 30 minutes at 90°C.

The vapor phase soldering process used was based on the method developed by Earl Nicewarner at Fairchild Space and Communications Corporation in Germantown, MD. A computer controls the elevator advancement, starting and stopping the elevator as a result of real-time temperature data from thermocouples that monitor the vapor and product temperatures. The computer is programmed to allow the elevator drive motor to be stopped during product heatup and to be restarted and stopped as a result of changes in the product's temperature. This process enabled heating slopes to be achieved within the maximum recommended limit of 4°C/second. Figure 1 contains a sample profile of a board reflowed with this method.

One board assembly was prepared using each of the above soldering methods and allowed to cool naturally, without forced air. The substrate material used in this study was FR4 glass/epoxy. The component package styles attached to the substrate included leadless capacitors (sizes 0805, 1808, and 1812), leadless resistors (sizes 1206 and 2512), and MELF resistors (size 2308). All samples were attached with tin-lead eutectic solder. RMA flux was

used in liquid, core, and paste form. The assemblies were cleaned first with isopropyl alcohol, then with 1,1,1-trichloroethane, and finally with Freon TES.

The assemblies were then cross sectioned with a diamond saw to isolate the individual components. The component itself was not cut. The cross sections were mounted and placed in a mold. A fast-cure, two-part acrylic epoxy was poured into the mold and allowed to cure. The samples were left undisturbed for a minimum of 30 minutes before the mold was removed. Once removed, the samples were allowed to set for a minimum of 4 hours prior to the grinding and polishing operations to prevent smearing. The grinding operation consisted of both rough and fine grinding. Rough grinding to expose the cross section of the joints was done with 220 mesh followed by 240 and 320 meshes. Fine grinding was done with 400 mesh followed by 600 mesh. Polishing was performed in two steps. First, the samples were polished with 6 μm diamond polishing compound with lapping oil. Then they were polished with 0.05 μm deagglomerated gamma alumina particles. Five to ten samples were produced per processing method.

After the samples were polished, they were optically examined under a high-powered microscope to observe the grain structure and voids. The frequency and location of the voids were noted for each solder joint. Photographs were taken of at least one joint per component. Then one sample from each method was coated with ~4.5 nm of gold to make it conductive for scanning electron microscopy (SEM) imaging. Photographs were again taken, along with dot maps and x-rays to identify the grain structure composition. The differences observed in the grain structure were quantified by computation of the lead-rich regions for each soldering method from digital images. A high-resolution CCD camera was used to transfer the SEM images to a digital format. These digital images were then processed so that the area of the voids and lead-rich regions could be calculated. The same magnification, solder joint location, and field of view were used on all samples. A few of the grain structures and their corresponding digital images are shown in Figures 2-4.

RESULTS

From the optical examination, the void distribution was recorded and the quantity and location of the voids were noted for each joint (Tables 1 and 2). The SEM images were digitized, which allowed the void sizes and the lead-rich regions to be calculated (Table 3). (The size of the lead-rich regions is an indicator of the grain size.)

When the data were compared within solder processing categories and among each other, some interesting results were discovered and confirmed. The traditional hand soldering process was included in the analysis for benchmarking purposes. It yielded the smallest grain structure of all the processes evaluated. It also had the second largest incidence of voids; however, the voids were among the smallest, averaging 54 sq. μm. In general, the soldering methods produced voids in the areas beside and under the chip component terminations, with 73% of the voids found in these regions.

TABLE 1. Void Distribution from Optical Analysis at 400X.

Method	Total No. of Voids	Av. No. of Voids Per Joint	No. of Joints	No. of Void Free Joints
VPS, paste uncured	67	4.19	16	1
Hand, rosin core solder	37	2.64	14	5
VPS, paste cured	26	1.44	18	7
Hand, paste cured	12	1.00	12	6
Hand, paste uncured	11	0.92	12	6
Hand, pre-tinned, no flux	4	0.29	14	10
Hand, pre-tinned, RMA flux	3	0.21	14	11

VPS, vapor phase soldering

TABLE 2. Void Location from Optical Analysis at 400X.

Location	Soldering Method							
	VPS, No Cure	Hand	VPS, Cure	Hand, Cure	Hand, No Cure	Hand, Pretin, Flux	Hand, Pretin, No Flux	Total
Beside termination	14	3	10	3	5	4	1	40
Under termination	40	29	6	0	1	0	1	77
Near termination, surface	0	5	0	0	0	0	0	5
Between term. and tail	4	0	4	0	0	0	0	8
Tail area, by pad	2	0	2	2	4	0	0	10
Termination and pad corner	7	0	4	0	0	0	0	11
Near surface, middle	0	0	0	2	0	0	1	2
Near pad, middle	0	0	0	1	0	0	0	2
Center of joint	0	0	0	2	1	0	0	3
Near termination, by pad	0	0	0	2	0	0	0	2
Total	67	37	26	12	11	4	3	160

TABLE 3. Void and Grain Structure Data from SEM Analysis.

Method	Average Size of Lead-Rich Regions (sq. μm)	Lead-Rich Region (%)	Average Void Size (sq. μm)
VPS, paste uncured	1.11	20	377
Hand, rosin core solder	0.93	19	54
VPS, paste cured	2.13	22	74
Hand, paste cured	5.81	22	22
Hand, paste uncured	2.21	25	76
Hand, pre-tinned, no flux	2.56	25	108
Hand, pre-tinned, RMA flux	1.80	22	92

EFFECTS OF CURING

The effects of curing on the frequency and size of the voids was most dramatic in the vapor phase soldering process. By curing the solder paste prior to reflow soldering, the number of voids was reduced by half and the void area was decreased by 80% (Figures 5 and 6). For the hand soldering processes that used solder paste (instead of the standard wire), there was no difference in the number of voids between cured and uncured processing, but the void size was reduced by 70%. Although the soldering methods that included curing had larger lead-rich regions, the tradeoff of the cure process is in the reduction in the number and size of the voids. Current testing will attempt to determine if fewer voids improves the fatigue life of solder joints.

We do not know why larger grain structures were found when the cured soldering methods were used (Figure 7). To determine if the curing process prior to reflow soldering slowed the rate of cooling, thermocouples were attached to two assemblies; one assembly was placed through the curing process and one was not. The assemblies were reflowed simultaneously in the vapor phase soldering machine. The cured assembly was removed from the oven and immediately placed in the machine. Figure 8 shows the reflow temperature profiles of the vapor phase soldering process. As can be seen from the profiles, there is no difference in cooling rates between the assemblies. In fact, when this test was repeated with solder paste instead of the typical presoldered joints, there still was no difference observed in the cooling rates (Figure 9). Because previous studies confirm that grain structure depends upon the cooling rate, no explanation can be given as to why larger grain structures were found in the soldering methods with curing. This is an area to be explored in the future.

PROCESS COMPARISONS

VAPOR PHASE SOLDERING COMPARED WITH PRE-TINNING

The grain structure of the vapor phase process with paste cure and the pre-tin/reflow processes was similar, but the pre-tin/reflow processes had the advantage of producing significantly fewer, albeit slightly larger, voids. In fact, the pre-tinned processes resulted in the fewest voids. Fewer voids may be caused from the repeated reflowing (or melting), which may allow more time for the gases to escape. Voids may also be converging during this process, resulting in the larger voids. Another possibility is that the average void size may not be the true size because the sample size is too small (three to four voids).

HAND WITH CORE COMPARED WITH PASTE SOLDER

Also interesting are the differences between hand soldering with solder wire and hand soldering with solder paste. The larger grain structure resulting from hand soldering with solder paste had not been anticipated. Because the vapor phase uncured process yielded a grain structure similar to that of the hand soldering process, the difference in solder form can be eliminated as a cause. The reason for the difference is unknown. The fewer voids in the processes using solder paste most likely are a result of the composition of paste system; it is composed of solder ball particles suspended in a flux/binder solution, which may allow more volatiles to escape from between the particles before its melting point is reached.

HAND COMPARED WITH PRE-TINNING

Solder iron reflow of pre-tinned components and substrate produced the fewest voids of any process evaluated. Specifically, it outperformed traditional hand soldering by yielding 1/10th the number of voids. The average lead-rich regions and void sizes with the pre-tinning process was approximately double that of traditional hand soldering, but is comparable to these same values for the vapor phase soldering process with cured paste.

CONCLUSIONS

The two variables of solder paste curing and soldering method are primary factors in void and grain formations, respectively. From the results the following conclusions were drawn:

- Curing the solder paste decreases the number and size of internal voids in a solder joint.
- The majority of the voids (73%) in chip component solder joints are concentrated beside or under the termination.
- Pre-tinning the components and substrate and reflowing without addition of solder significantly reduced the void frequency. However, in comparison with traditional hand soldering, the grain structure and void sizes doubled. Temperature cycling tests in progress will determine the effect, if any, on fatigue life.

- The pre-tin/reflow processes and the vapor phase process with cured paste had similar grain structures, but the pre-tin reflow processes had the advantage of producing significantly fewer, albeit slightly larger, voids. Further tests are being performed to determine if this difference is significant.
- Curing the paste prior to vapor phase solder reflow produces significantly fewer voids that are 1/5th the size of those produced without solder paste curing.

As a result of this study, four soldering methods were selected for further analysis, which will include temperature cycling. Two of the methods will include the pre-tinning process because it yielded the lowest incidence of voids. This next round of testing will attempt to provide the data necessary to determine the effects of voids and grain structure on the fatigue life of the solder joint.

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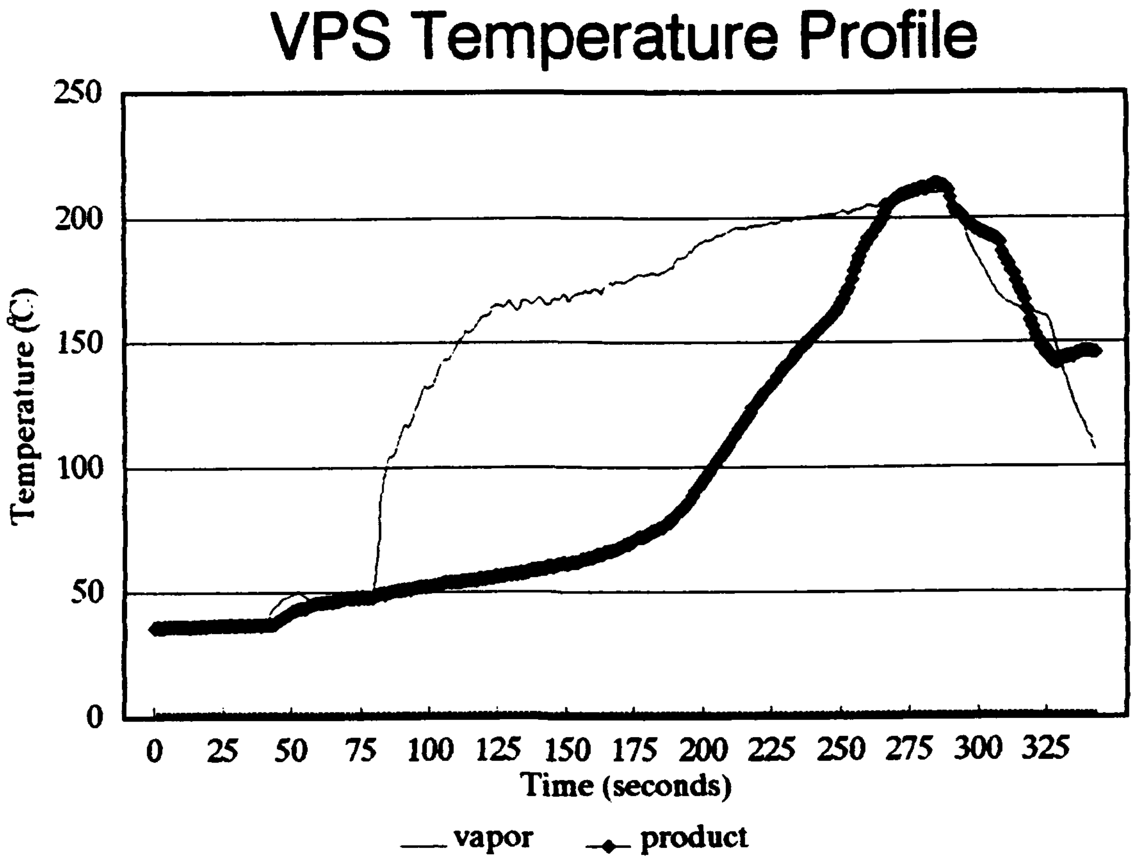

LABTECH NOTEBOOK File0018.WK3
TEE-710 S/N 004 rflw52.prn
The time is 17:20:44.79.
The date is 9-16-1992.

Max Temp(C)	213.92
Max Slope	4.31
t > 183 C	54 sec

FIGURE 1. Sample Reflow Temperature Profile of an Assembly Processed in the Computer-Controlled Batch Vapor Phase Soldering Machine.

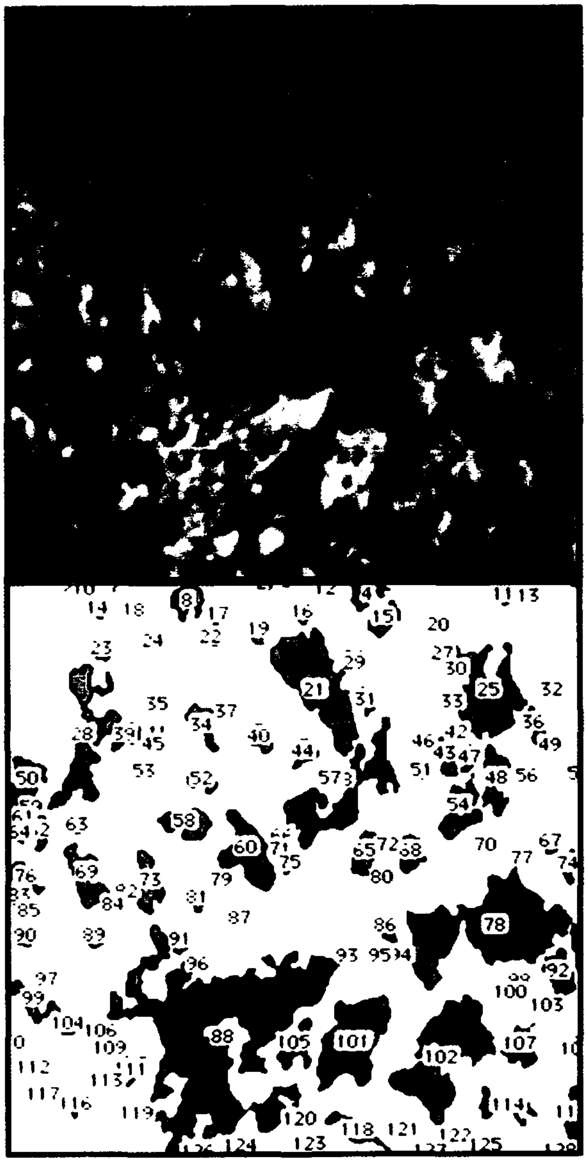

FIGURE 2. SEM and Digital Image of a Hand Soldered Joint Using Traditional Tin-Lead Eutectic Cored Solder.

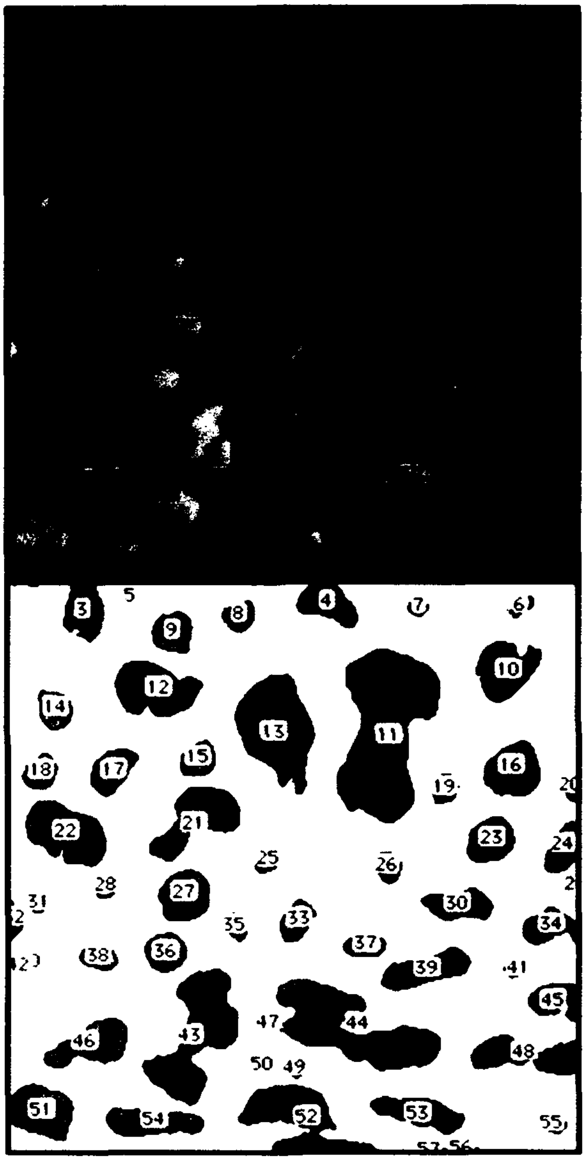

FIGURE 3. SEM and Digital Image of a Vapor Phase Soldered Joint Without Solder Paste Curing.

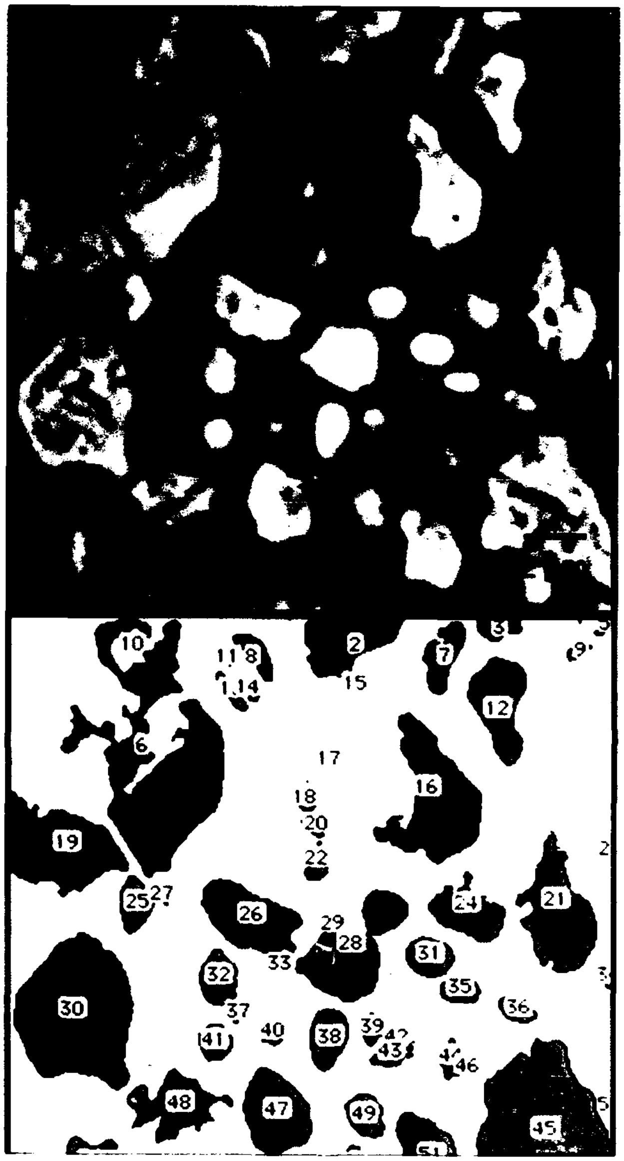

FIGURE 4. SEM and Digital Image of a Hand Reflow Soldered Joint Using the Pre-tinning Method Without Liquid Flux.

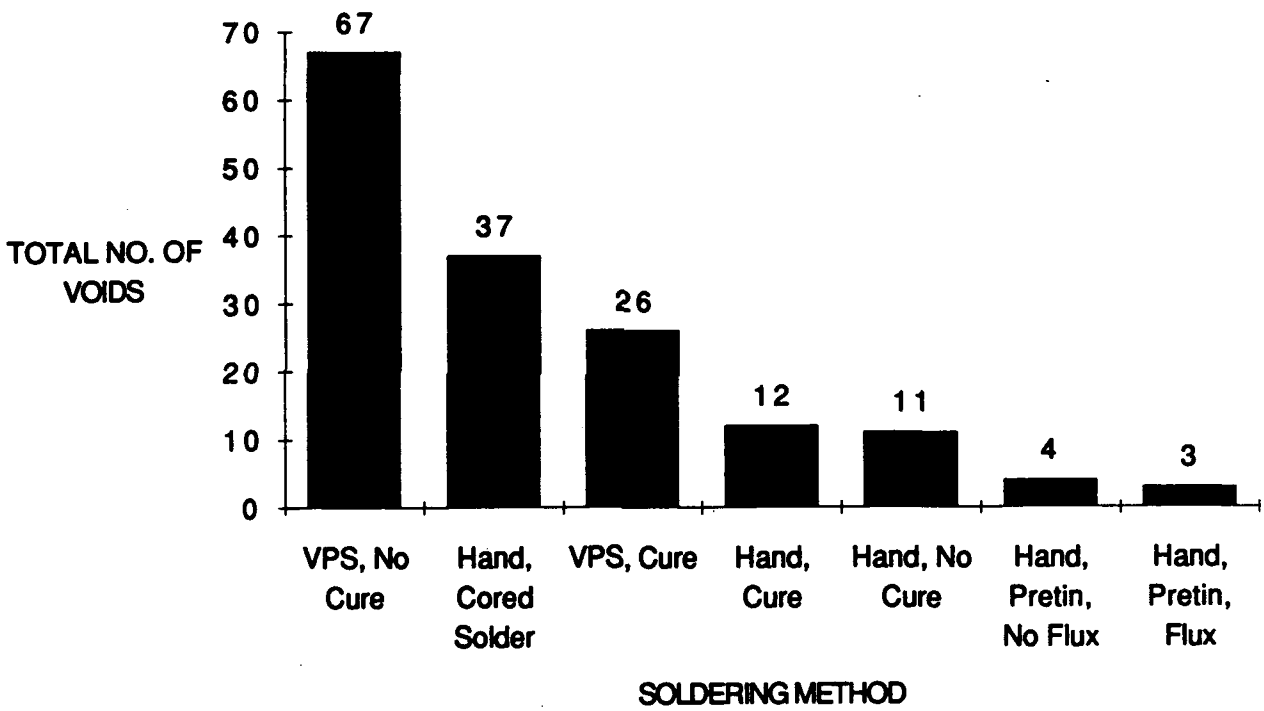

FIGURE 5. Frequency Distribution of Internal Solder Joint Voids by Soldering Method.

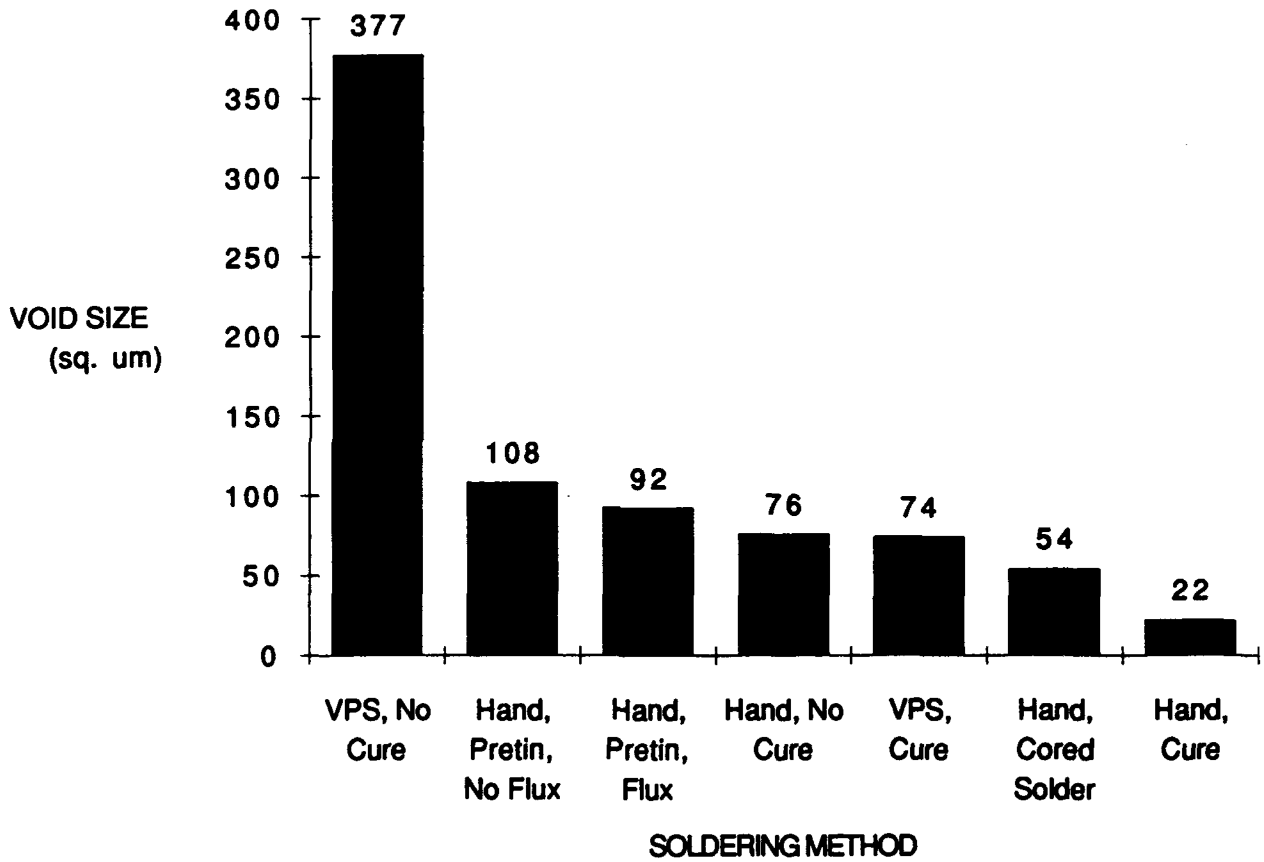

FIGURE 6. Average Void Size by Soldering Method.

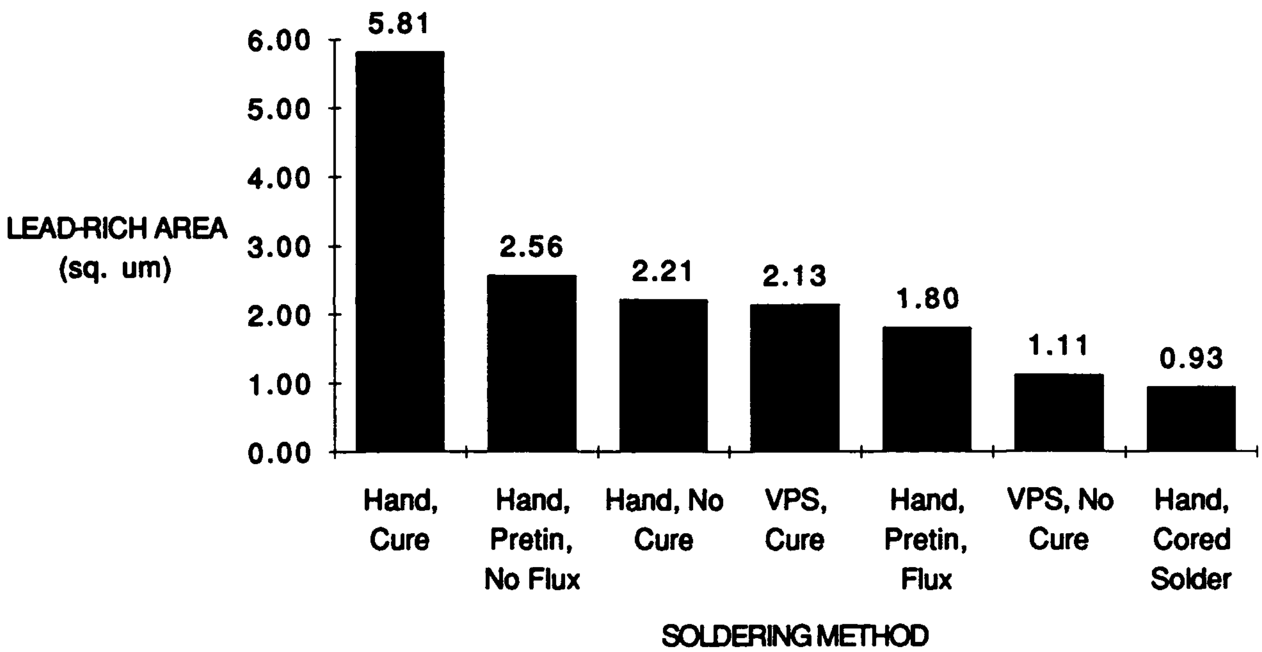

FIGURE 7. Average Size of Lead-Rich Regions by Soldering Method.

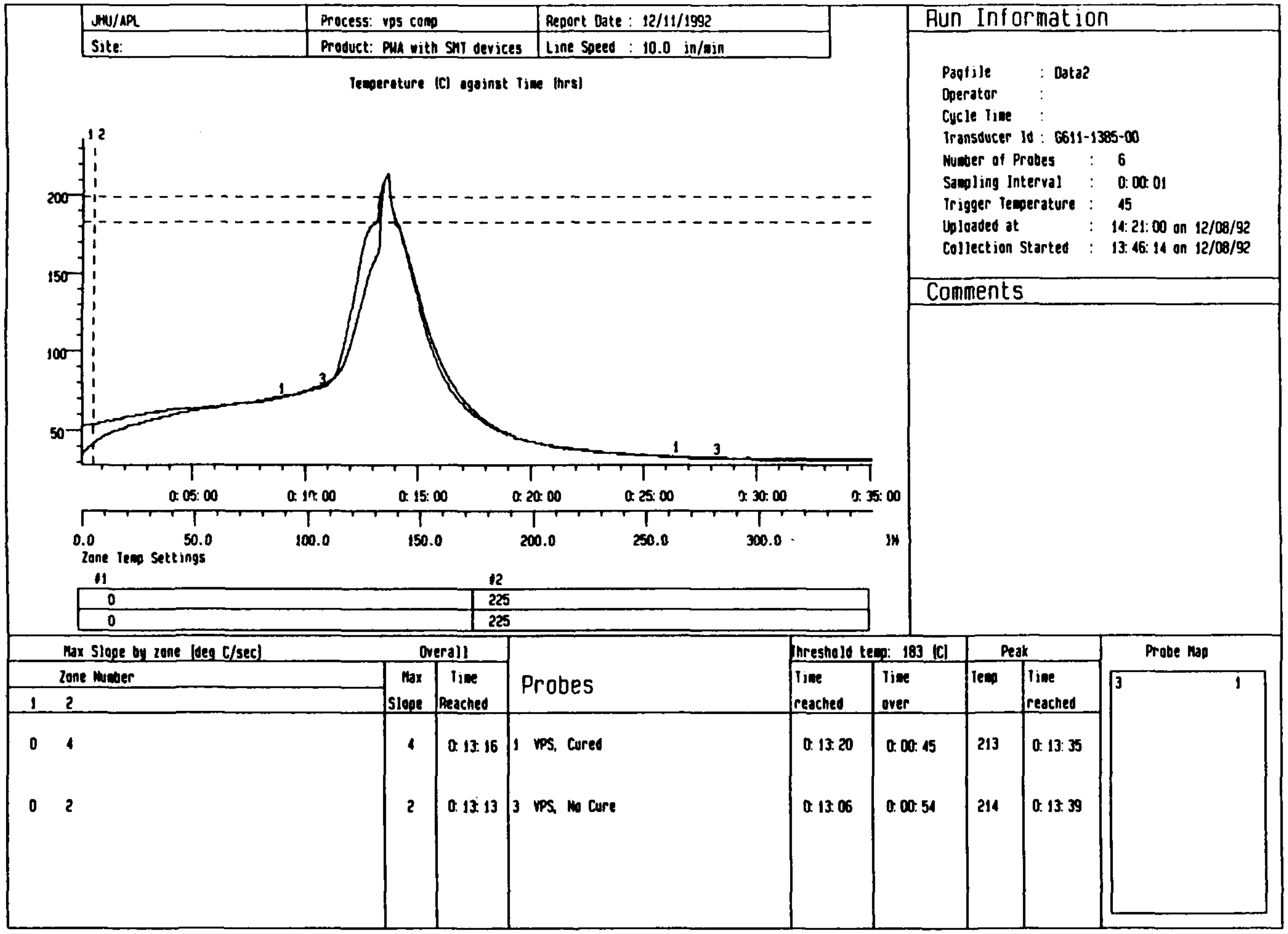

FIGURE 8. Vapor Phase Reflow Soldering Profiles of Two Assemblies: One With Curing and One Without

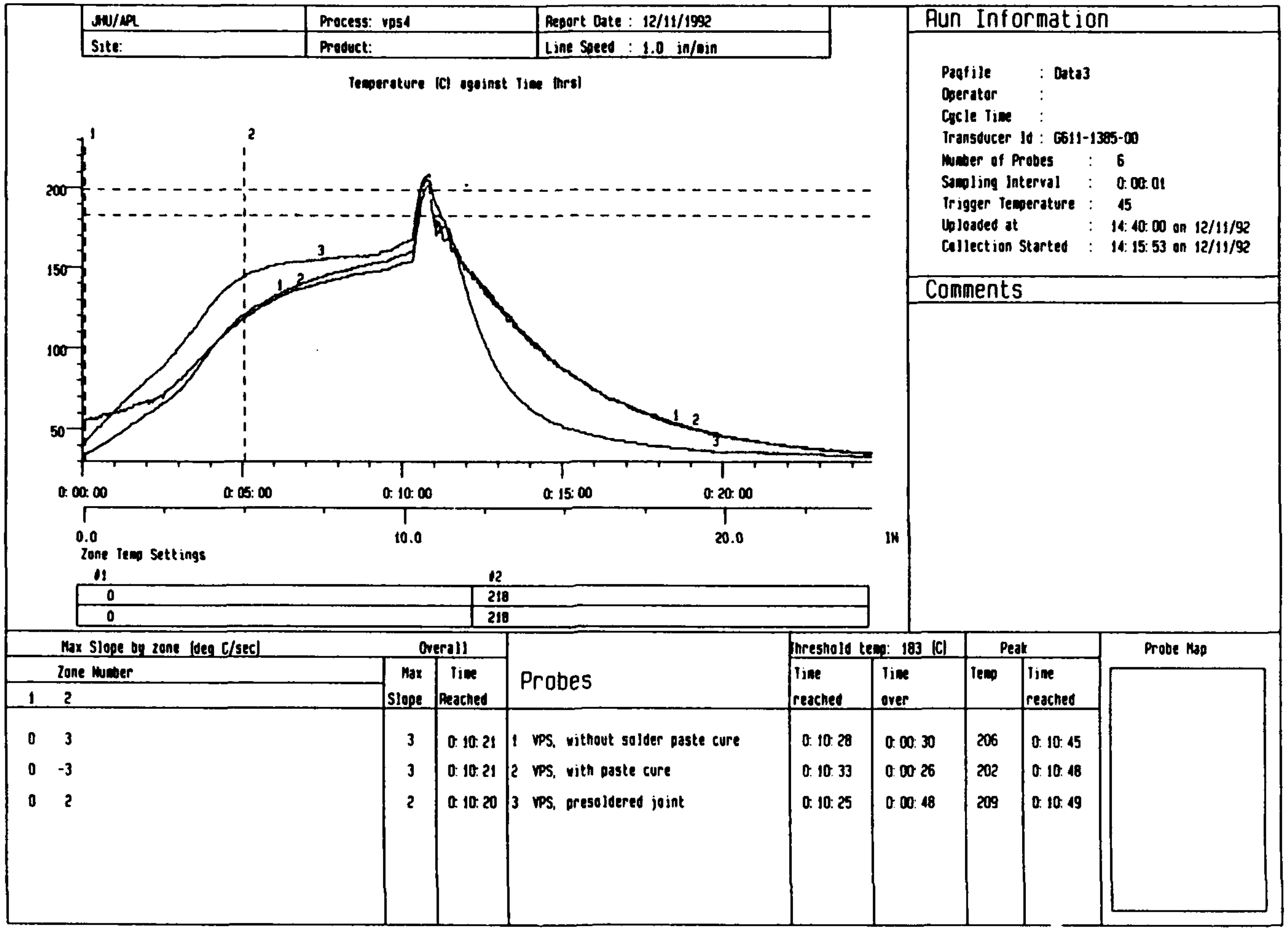

FIGURE 9. Vapor Phase Reflow Soldering Profiles of Three Assemblies: One With Solder Paste Curing and One Without, and One Presoldered

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FROM PRODUCT TO PROCESS IN ELECTRONICS QUALITY

by

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ABSTRACT

Defense electronic manufacturers have traditionally labored to meet their quality requirements by attempting to inspect quality into each individual product. Today, it is understood that in order to survive, the quality focus must be on process control and continuous improvement.

The task that currently awaits many firms is the transition from a product-oriented quality system to a process-oriented quality system. The system change must be accomplished without impacting the company's ability to meet production schedule or contractual quality requirements. In the current Defense environment of shrinking budgets, high product mix, and low volume production, such a change can be a very difficult proposition.

This paper outlines the methodology involved in the transition from defect detection to defect prevention, and how individual Statistical Process Control (SPC) tools can be integrated into an effective process quality system.

INTRODUCTION

Variability is inherent in all processes. At almost any level it causes product degradation and loss of resources and income. The traditional system of quality is based upon a set of specification limits representing a specific amount of variability that has been deemed acceptable. Any product that does not fall within specification limits is categorized as defective. This product-oriented system relies on inspection methods to discover all defects on an individual product basis.

A product-oriented quality system does nothing in itself to reduce or eliminate the cause of defects. It does not improve the product, increase manufacturing capability, or reduce cost. Since this type of system does not facilitate improvements at the process level, increasing quality simply means scrapping and reworking a

greater percentage of the product. Thus, in this system higher quality actually means lower profitability. In order to remain viable in today's environment, a manufacturer must employ a quality system that does more than detect individual defects at the product level.

The focus of an effective quality system must be on the process, rather than the product. A process-oriented quality system focuses on the creation of robust manufacturing processes and applies statistical methods to further reduce process variation. A quality system that eliminates process variability reduces costs and increases manufacturing capability, therefore improving profitability.

The process quality system employs Statistical Process Control (SPC) methods to identify special causes of variation from common causes of variation. The identification of common causes from special causes is necessary because they must be treated in a different manner to be successful. SPC is also used to indicate priorities for process improvement efforts since all processes experience variation in differing degrees.

BACKGROUND

The ideas discussed in this paper are related to events which took place between December 1990 and May 1992. The facility was one that used a combination of manual and automated methods to produce electronic assemblies for Defense applications.

The assemblies produced were not all governed by the same quality specifications, however. Some product lines were subject to very highly structured, inspection intensive quality requirements, while others were not. For some products, nearly every operation was followed by a quality inspection, and then a customer inspection. On the other hand, there were product lines which did not have nearly the same high level of inspection, or customer representative activity.

Initially, the working environment was such that the manufacturing, quality, and customer objectives were not necessarily aligned with each other. Many activities were non-value added tasks perpetuated by tradition or other departmental reasons. The result of this condition was a disjointed quality approach that was not always conducive toward improving quality. An objective was set to re-define the quality tasks across all product lines. The intent was to structure quality activity in a way that would be value-added and facilitate continuously improving process quality. Effort was made to examine tasks for their "value" toward improving overall process quality. If the value wasn't apparent, the tasks were modified or discontinued. By striving to reduce variation for all products beginning at the process level, it would also be possible to meet the differing product quality requirements in a more efficient manner.

TRANSITION

METHODOLOGY

Although the benefits of a process-based quality system versus a product-based system may be apparent, the method for transition may not be. In order to convert a quality system from product to process, the macroprocess used to produce the product must be broken down into microprocesses. Each product possesses certain attributes that control its ability to meet the customer's expectation. These product attributes must be identified. The microprocesses that influence or control those attributes become the focus of the process quality system.

Once the product attributes have been identified, the microprocesses responsible for those attributes can be isolated. For each microprocess, the causal relationships between the process factors and the process response, or results, must be explored and determined. Ideally, this is done using a process optimization method such as Design of Experiments (DOE). Following this, the process factors become the primary indicators for quality rather than the product itself. The objective for isolating process factors is to identify a variable response that can be measured and monitored before and during production rather than inspecting product attributes after the process is finished. Automated or machine type processes may need to be broken down several times until a source of variable data can be identified.

AUTOMATED PROCESSES

An illustration of process monitoring rather than attribute inspection can be made with the circuit card assembly process. Instead of inspecting a circuit card product for wrong parts, poor solder, etc., the assembly macroprocess should be reduced down into microprocesses. One microprocess that comes to mind is the solder process.

In this example, the circuit cards are wave soldered. When examining the solder microprocess, it is apparent that there are several critical factors to consider. Once critical factors such as flux density, preheat temperature, and conveyor speed have been identified, the process should be optimized. If DOE methodology is used, it is possible to optimize the process for a single product, or determine the optimum factor levels for all circuit cards in production. After the optimum settings have been found, they can be monitored to assure high quality before any product is actually produced.

Quality personnel are assigned to perform the value-added tasks of assisting in process optimization, monitoring, control, and documentation. In this way, Quality works with Manufacturing to accomplish the common objectives of increasing process capability and throughput. In contrast with the traditional "operation-inspection-

rework" method of quality, the reward for implementing quality at the process level is that higher quality no longer means higher costs and lower profitability. Through the reduction of process variability and elimination of scrap and rework costs, higher quality now means increased profitability for the company.

MANUAL PROCESSES

In the case of manual processes, it is not always possible to monitor the process without doing some type of product inspection. As with the automated process, the critical process factors must be identified based on the required product attributes. A determination has to be made as to the process factor and product attribute defect relationship for each factor and attribute. Inspection should be performed in a manner so as to gather data which can be used to statistically evaluate the capability and control of the process.

For instance, cables and harnesses are usually built using manual processes. Unfortunately, this means inspecting for attributes at the product level. However, inspection and documentation can be organized in a way that will utilize SPC methods to show the degree of process control and capability.

When developing an inspection-based SPC system, the first priority is to organize the reporting format to reflect the product defect-process factor relationship. This is done by organizing the defect reporting so that the defects discovered reflect the process status. Some contracts require complete defect traceability down to all sub-assemblies. In that case, the system would have to provide a means for product traceability as well as organizing the defects into process indicators. There are several software networking tools available, desktop or portable, that will do this automatically. In the absence of such tools, a paper-based system can be used.

The benefit of the computer network is basically the ability to accept data from different locations and compile it quickly. In order for a manual SPC tool to be useful, it must also be able to accept information from various sources and reflect process status without requiring off-line calculations. The format must be designed so that the vital process information is available instantly to all who are responsible for those processes.

The tool that seems to work best is a combination P-chart and Histogram which has been named the "Real-Time Process Control Chart". It is basically a matrix which has process indicator defect types down the left side and part number, quantity, and serial number information across the top (Figure 1).

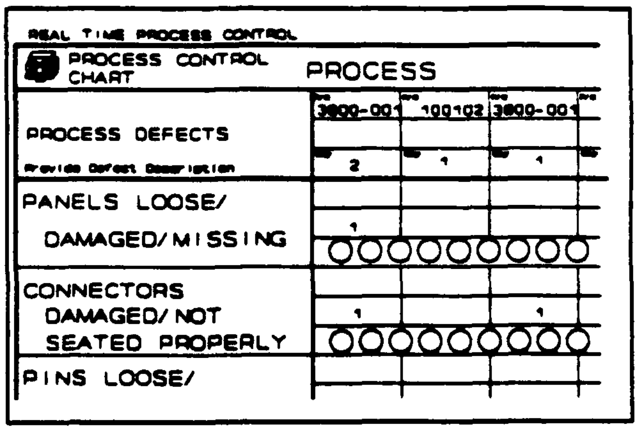

Figure 1. Defect Reference

The defect reference listing, defined jointly by production and quality, identifies defects which have been determined to be process indicators. The defect record area facilitates easy recording of defects and provides the traceability to each unit or sub-assembly.

The cumulative process defect history is recorded by filling in the circles for the correct process indicator. This becomes a process Histogram as the data is entered from individual product inspection. It provides the operators, inspectors, and supervisors with instant process awareness (Figure 2).

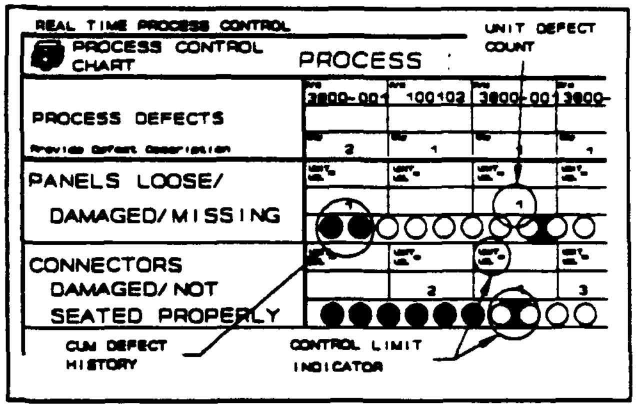

Figure 2. Defect History

Control limit indicators for both individual units and processes indicators are calculated from standard SPC equations and displayed on the chart.

When an unstable process is apparent, or a defect count exceeds a control limit, the need for corrective action is indicated. A space on the chart is reserved across from each process indicator for noting cause, actions taken, persons responsible, or further activity (Figure 3). This information may be kept somewhere else as well, but is vital to show the operators the status of actions taken on process problems.

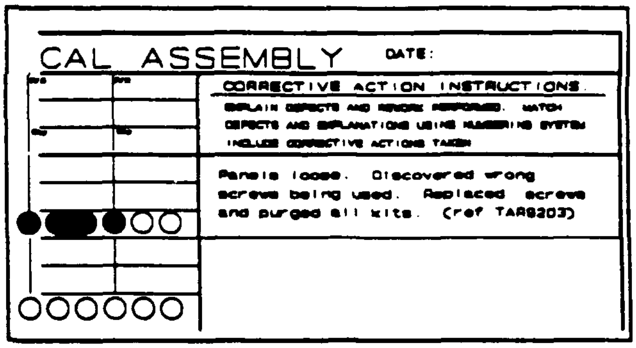

Figure 3. Corrective Action

Often one process produces different products in quantities that change from day to day. If the process is manual or can only be measured using attribute data, the process capability is generally measured in defects per million opportunities (DPM). Normalizing attribute data is necessary particularly when the process output varies in terms of volume or complexity. It is done by determining the number of defect opportunities for each product type, based on the type of defects that can occur, and their causes. Measuring attribute data in DPM puts dissimilar processes on even grounds for comparison and enables accurate assessment of process capabilities.

Attempting to normalize by labor hours, or some other factor not actually related to the specific process, is not beneficial. Once the normalizing figures have been developed according to the process and its output, process performance will no longer appear to vary according to volume or product mix.

Product inspection information can also be used with time and cost standards of rework to generate Cost of Quality figures. Each defect type can be classified in terms of production and quality time and cost for rework. This information is then coupled with inspection data to accurately compute the Cost of Quality.

CORRECTIVE ACTION FLOW

As stated earlier, one of SPC's functions is to identify special causes of variation from common causes of variation for a process. A control chart uses control limits to indicate when a special cause of variation is present. Special causes are present whenever the process output falls outside of the control limits. This is a signal for immediate correction, or the suspension of process activity until the correction can be made.

By definition, special or assignable causes of variation are more obvious than common or unassignable causes. Process capability is a measurement that is used to determine the extent of common cause variation. Common cause variation is often present in excessive levels even when process output falls well within the control limits. Specifically, process capability measures the degree of variation and how it affects the process output with respect to specification limits.

Since common causes of variation are usually more subtle than special causes, it is important to approach them in a specific manner. The correct method for identifying and eliminating them ordinarily requires management support and a cross-functional group. Failure to identify the cause accurately before attempting corrective action usually results in process "tampering" and often lowers process capability further.

Although it is important that processes not be degraded unwittingly through tampering, it is also important that continuous improvement opportunities be investigated regularly. Variability is present in any process, and has a cost. Any opportunity to reduce it is valuable and should be investigated.

Oftentimes formal documentation is only required by the customer in the case of continuing or significant problems. However, it is beneficial to use a database tool to document critical measurements for all processes at the end of each reporting period. In this way, a process history can be maintained and used as a reference. This information is useful for establishing performance baselines for new products or for research in the event of process difficulties.

CONCLUSION

Attempting to establish a quality system separately on individual products is not an effective way for a company to lower costs and improve quality. By basing the quality system upon the processes, it is possible to increase profitability by lowering costs and increasing manufacturing capability through reduced process variation. Long-term survival in all industries depends on the ability to control processes and continuously improve.

Without the proper methodology, process control and continuous improvement are merely ideas. Products and processes differ from one to another, but the means for controlling and reducing variation among them are the same. The relationship between product attributes and the process factors that affect them is the key, and must be the focus of the Quality effort. The companies who strive for lasting, continuous process improvement and design their quality systems to facilitate it, will be the ones who have the best chances to survive.

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CONTAMINATION OF SOLDER JOINTS CAUSED BY ULTRASONIC TINNING

by

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ABSTRACT

There is a need for ultrasonic fluxless soldering of electronic components. Ultrasonic soldering can be accomplished without the use of flux which eliminates subsequent flux residue cleaning operations. During an experiment to refine the process for a particular application, several solder joints were produced by tinning stranded insulated wire in an ultrasonic solder pot. Microscopic analysis revealed the tinned wires were contaminated with metallic particles. Examination of the solder pot showed evidence of cavitation erosion. Further evaluation of the tinned wires pointed to the solder pot as the source of the contamination. This paper documents the contamination problem.

TINNING PROCESS REFINEMENT DISCOVERS CONTAMINATION

To meet contract requirements for tinning components and stranded wire, a new tinning process was needed. The current method used for tinning in the factory caused excess solder wicking underneath the wire insulation. Ultrasonic tinning was evaluated as a possible replacement for conventional tinning to eliminate the wicking problem.

An experiment was conducted using silver plated, Teflon insulated, multistrand wire. The experiment was developed using Taguchi Design of Experiments. An array called an L9 was used. The array allowed nine different trials by varying four different parameters: 1) Two different depths for dipping the wire into the solder; 2) Two different nitrogen pressures for the gas blanket over the top of the solder bath; 3) Three different wire gage sizes; and 4) Three durations of wire immersion in the ultrasonically agitated solder.

The process used to tin the wires is as follows.

1) Start the nitrogen blanket gas flow by stepping on the nitrogen gas switch.

2) Immerse the wire to be tinned in the solder bath to the desired depth. In the case of this experiment, it could have been dipped either to the edge of the insulation (100%) or a little deeper (120%). Normally, the desired depth will be only to the edge of the insulation.

3) Immediately after immersing the wire in the solder, activate the ultrasonic energy. The ultrasonic energy is set at maximum power intensity. The time the ultrasonic energy was on is a parameter above and varied from 4 to 8 seconds.

4) Hold the wire in the solder bath until the ultrasonic energy shuts off automatically.

5) Remove the wire from the solder pot.

6) Identify individual samples.

The array controlling the experiment is shown in Figure 1. Nine different combinations of the four parameters were used in the experiment. The various combinations of the parameters used will, when mathematically analyzed, tell us the best combination of the parameters to successfully tin the wires.

After the wires were tinned in the nine various combinations, they were cross sectioned and evaluated for wicking and solder voids. It was during this part of the evaluation the contamination in the solder joints was found. The evaluation of the cross sections was performed on an optical microscope. The cross sections were photographed. Figures 2, 3 and 4 show the typical cross sectioned wires that are the result of the tinning experiment. Two samples are shown in each figure. The one on top is the first end of the wire dipped in the solder. The bottom sample represents the other end of the same wire after tinning.

During the course of the solder pot installation and start-up prior to production, one major notable problem became apparent. The solder in the pot quickly became contaminated with iron beyond the limit allowed by Mil-Std-2000. The source of the contamination was suspected to be the stainless steel solder pot itself.

The solder pot had, prior to this experiment, overheated due to a stuck relay. The control indicated a peak temperature of 948°F during the event. This temperature (948°F) is within the temperature range which will sensitize Type 304 stainless steel (reported by vendor as the material used for the solder pot). Subsequent evaluation of the solder pot showed the stainless steel had, in fact, been sensitized. This sensitization phenomena increases the materials sensitivity to corrosion, particularly in the grain boundaries.

Microscopic examinations of the tinned wires showed particles to be present as a contaminant in the solder. Further analysis showed these particles to be equivalent in composition to the 304 stainless solder pot. It is apparent the ultrasonic energy applied to the solder in the pot is attacking the base metal of the pot, and the contaminants in the solder are from the pot itself.

Figure 5 is a photo looking down onto the bottom of the solder pot. Cavitation damage is evident in the areas directly above the ultrasonic transducers and in the surrounding areas. Area 3 in Figure 5 is the area of the worst cavitation damage.

Extensive cavitation damage is shown in Figure 6. This is a closer view of Area 3. The cross section was taken in this area to be studied in greater detail. Figure 7 shows the area after it was sectioned with a band saw.

A side view of the cross section is shown in Figure 8 looking at Area 3. The apparent loss of metal is easily seen. Point "D" was examined in greater detail. Point "E" was also looked at separately. Figure 9 shows Point D magnified 100 times. Cavitation damage is evident. Figure 10 of the same cross section shows cavitation damage at Point E.

Another area of the pot was subjected to a sensitization test to see if grain boundary attack was evident. Figure 11 shows the steel pot liner has been sensitized and grain boundary attack is present.

A new solder pot was installed to replace the sensitized liner. The attack of the pot by ultrasonic cavitation is still a factor of concern and will have to be monitored. The iron content in the new pot will rise much faster with the use of the ultrasonic energy compared to a standard solder pot. The 304 stainless steel in the new pot liner will be under scrutiny.

Evidence already points to the fact that stainless steel particles are becoming encapsulated in solder joints of tinned wires. A tinned wire was cross sectioned and examined under the electron microscope. Figure 12 shows the presence of metal particles in a solder joint. Figure 13 shows the presence of metal particles in the solder itself. A sample of solder was drawn from the solder pot, cross sectioned, and examined on the scanning electron microscope. Elemental analysis using energy dispersive spectroscopy (EDS) determined the particles to be stainless steel.

If the new pot liner fails through cavitation (i.e. the solder becomes contaminated with iron), it will have to be replaced with a cavitation resistant alloy.

Three solder samples have been taken since the pot has been released to production. One of the samples was of unused ultra-pure certified solder taken out of the pot before any use occurred. The solder pot controller has an hour meter built into the control panel. The hour meter records the amount of time the ultrasonic energy has been turned on while the solder pot is running. The pot was filled with fresh solder when the hour meter was at 592.0 hours. Monitoring of the solder continued until it was determined the solder was out of specification, as far as the iron content was concerned. The limit was reached at 596.5 hours. At this point, the solder was discarded and the pot refilled with new solder. Before the pot was refilled, the bottom of the pot was visually inspected and some very minor cavitation damage was suspected.

Chromium, nickel and iron are the major constituents of stainless steel with iron being the major chemical element in the steel. The solder sample after 4.5 hours of ultrasonic run time was showing the presence of stainless steel contamination. Iron and nickel are listed in Mil-Std-2000 as solder contaminants. Iron has a maximum limit of 200 ppm and nickel has a limit of 250 ppm. Chromium is not listed in the specification. It is not commonly found in solder, and therefore, not listed as a contaminant.

The solder should be maintained with chemical composition checks for every hour of ultrasonic run time to track the erosion of the stainless steel pot. Once a baseline has been established as to the rate of erosion, a decision can be made as to how often the solder should be replaced, and/or how often the solder pot liner should be replaced or a different alloy tried.

FIGURE 1. Taguchi L9 Experiment for Ultrasonic Tinning

Trial	A = Wire Dip Depth	B = Nitrogen Pressure	C = Wire Gage	D = Immersion Time
1	1	1	1	1
2	1	2	2	2
3	1	2	3	3
4	2	1	2	3
5	2	2	3	1
6	2	2	1	2
7	2	1	3	2
8	2	2	1	3
9	2	2	2	1
Key:	1 = 100% Depth 2 = 120% Depth	1 = 40 psi 2 = 60 psi	1 = 12-gage 2 = 14-gage 3 = 16-gage	1 = 8 Seconds 2 = 6 Seconds 3 = 4 Seconds

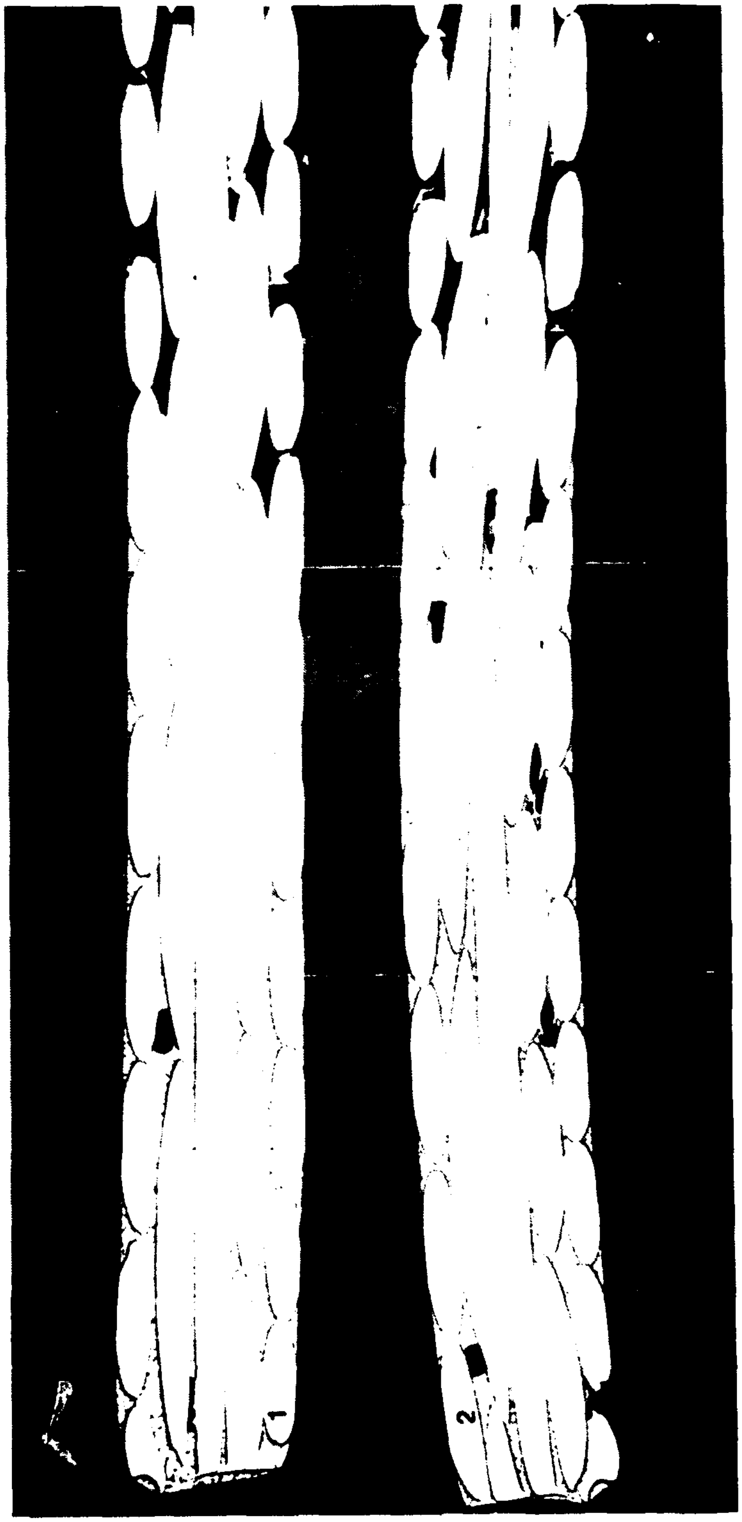


FIGURE 2. Trial Number 6. Magnification: 12.8X. Dip depth 120%, 60 psi nitrogen pressure, 12-gage wire, 6 seconds.

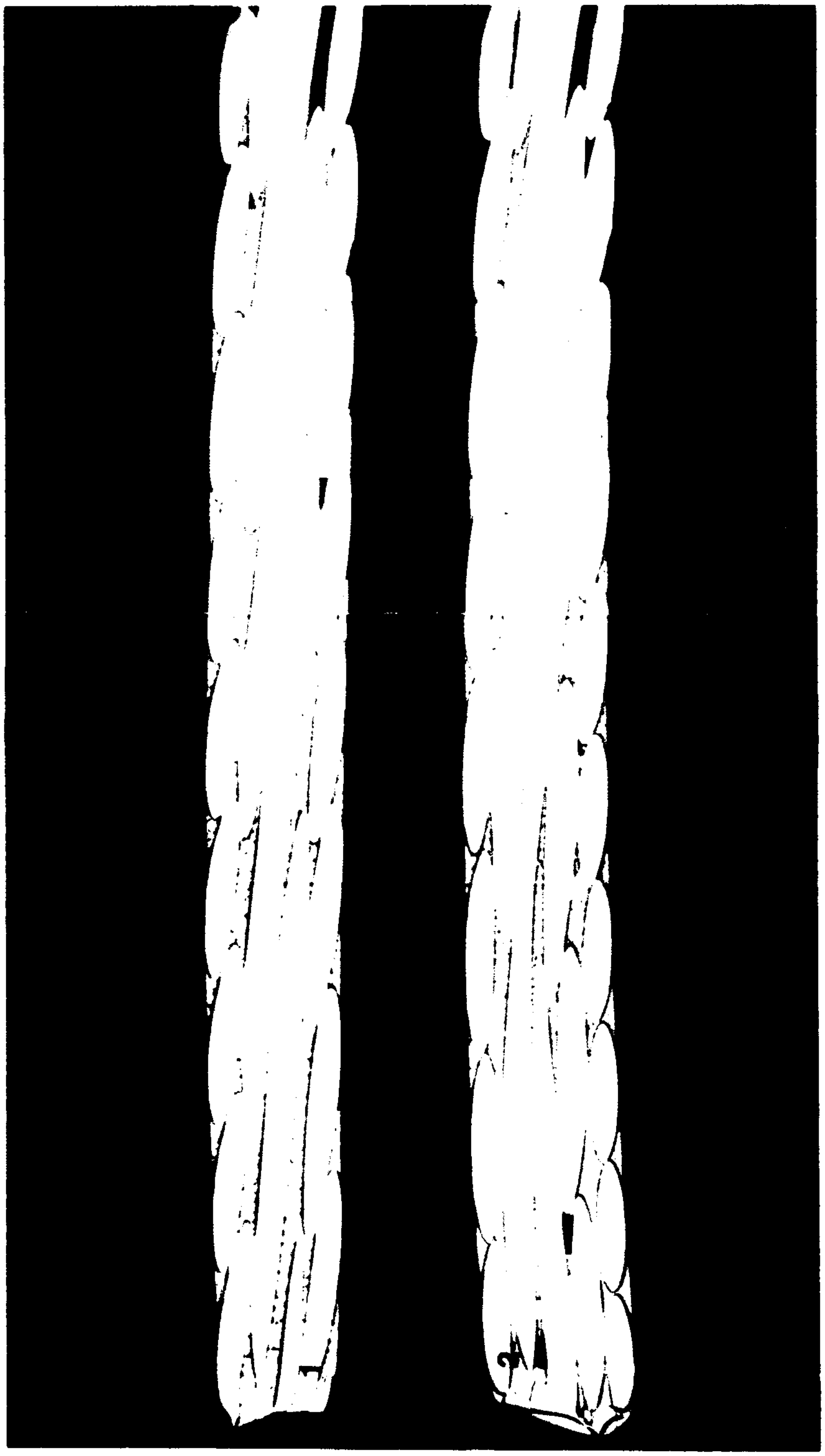


FIGURE 3. Trial Number 2. Magnification: 12.8X. Dip depth 100%, 60 psi nitrogen pressure, 14-gage wire, 6 seconds.

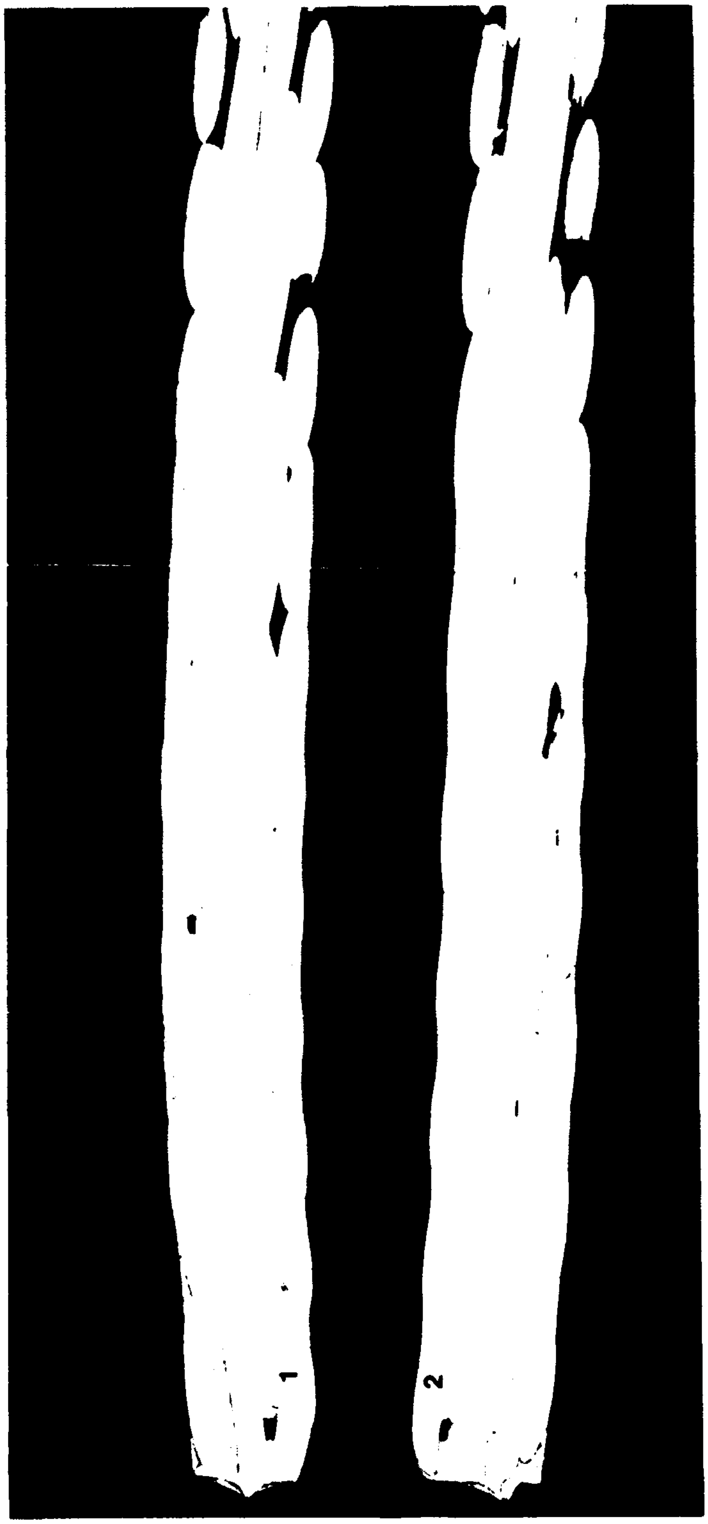


FIGURE 4. Trial Number 4. Magnification: 12.8X. Dip depth 120%, 40 psi nitrogen pressure, 14-gage wire, 4 seconds.

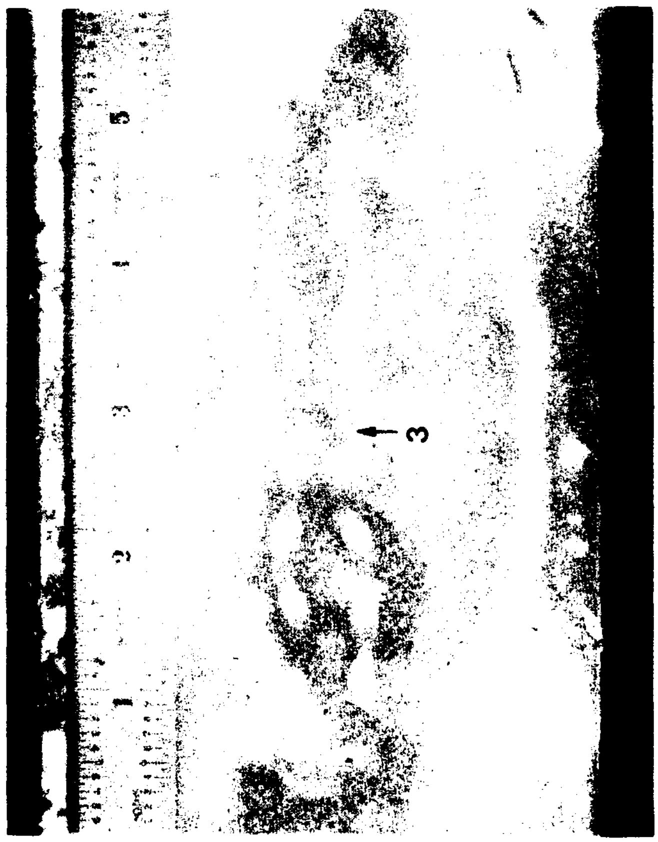


FIGURE 5. View of cavitation damage on bottom of pot over transducers. Area 3 is the worst cavitation damage.

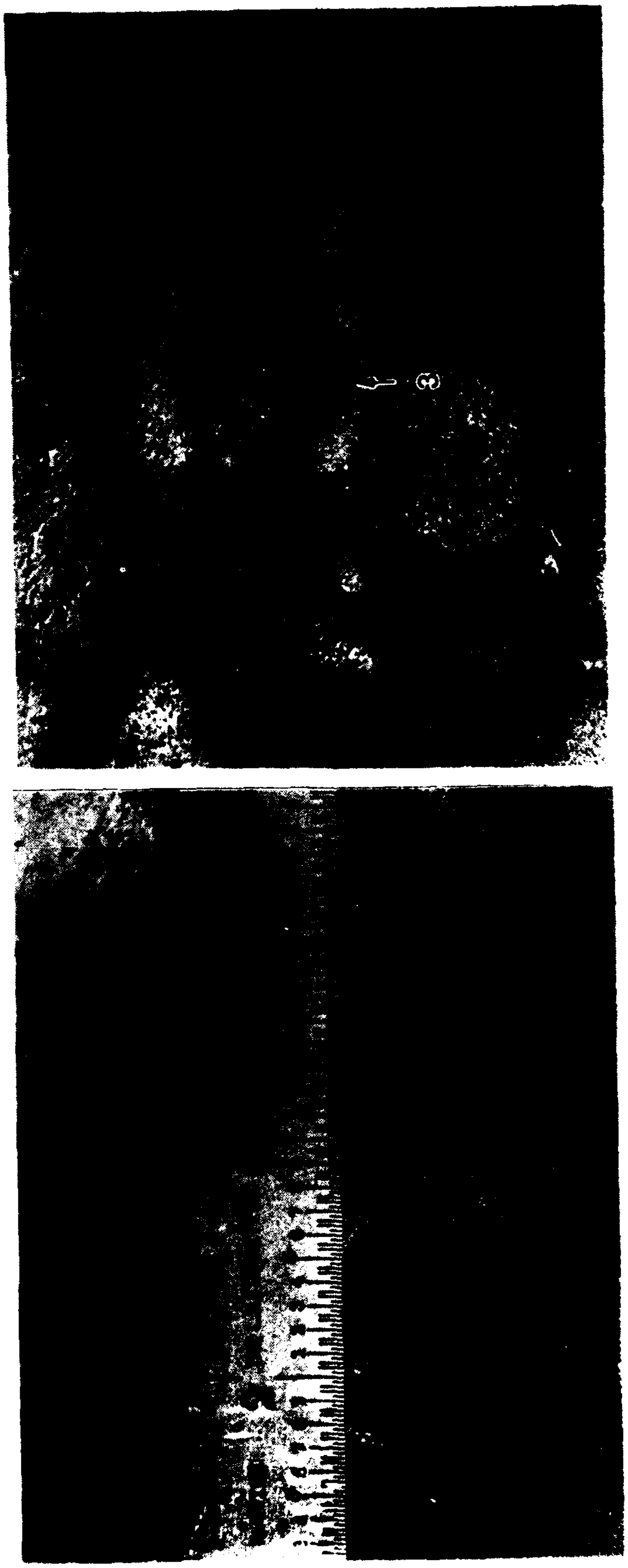


FIGURE 6. View of cavitation damage on bottom of pot over transducers. Area 3 is the worst cavitation damage.

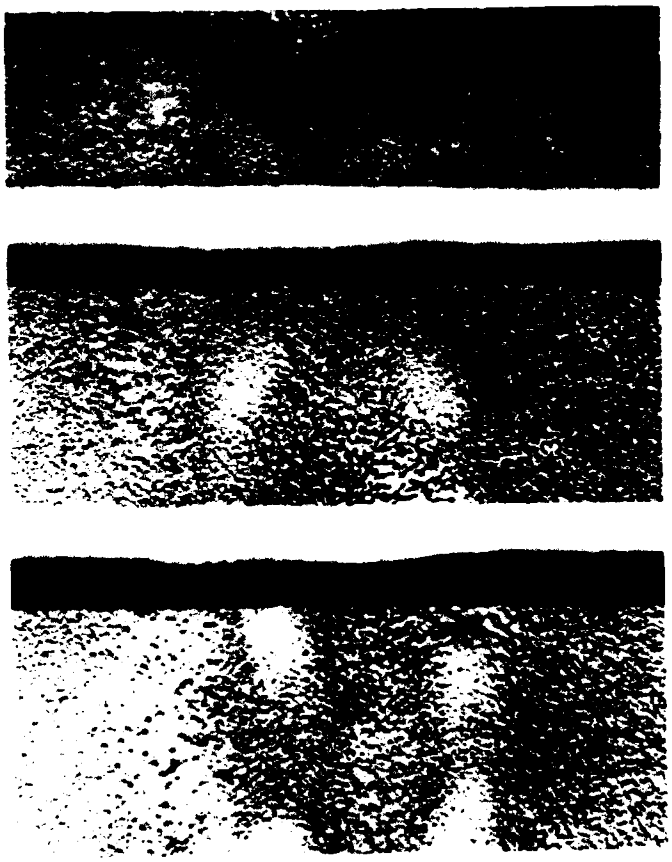
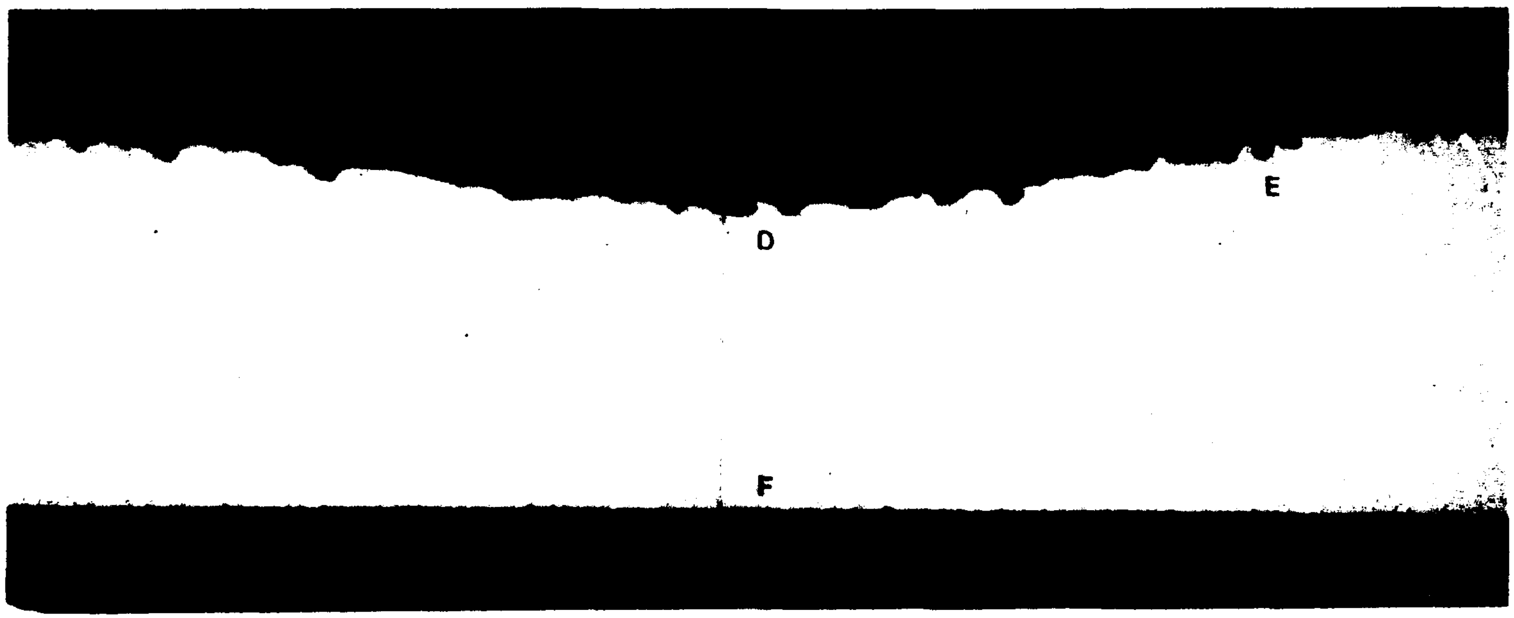


FIGURE 7. View of bottom of pot after sectioning. Magnification: 2.3X.

Solder Side



Bottom of Pot

FIGURE 8. Sampled Area 3. This area is directly over the center transducer which is mounted on the bottom of the pot. Note points D, E and F. They are looked at in detail in the following figures. Material loss is greatest in this sampled area. Magnification: 12.8X.

Solder Side

Bottom of Pot

FIGURE 9. Sampled Area 3, Point D. Magnification: 100X.

Solder Side

Bottom of Pot

FIGURE 10. Sampled Area 3, Point E. Magnification: 100X.

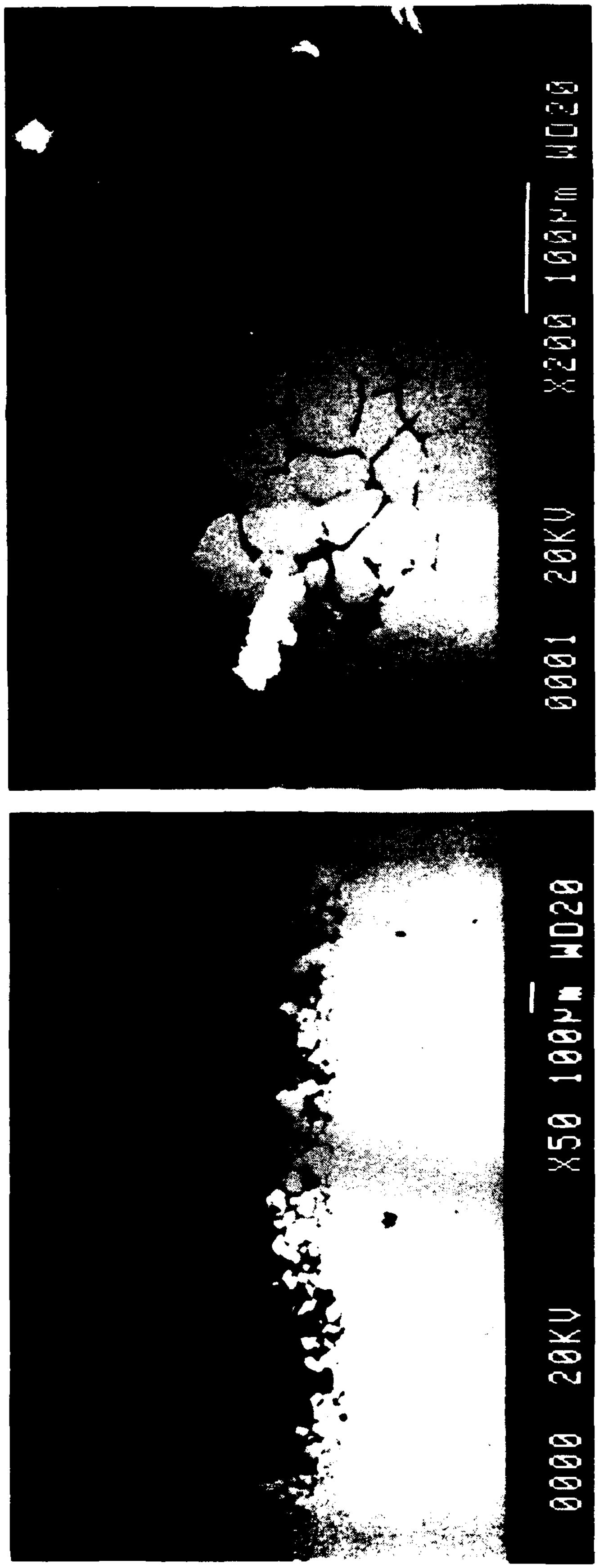


FIGURE 11. Scanning electron microscope photos showing grain boundary attack. Stainless steel has been sensitized due to excess heat. Magnifications: 50X and 200X, respectively.

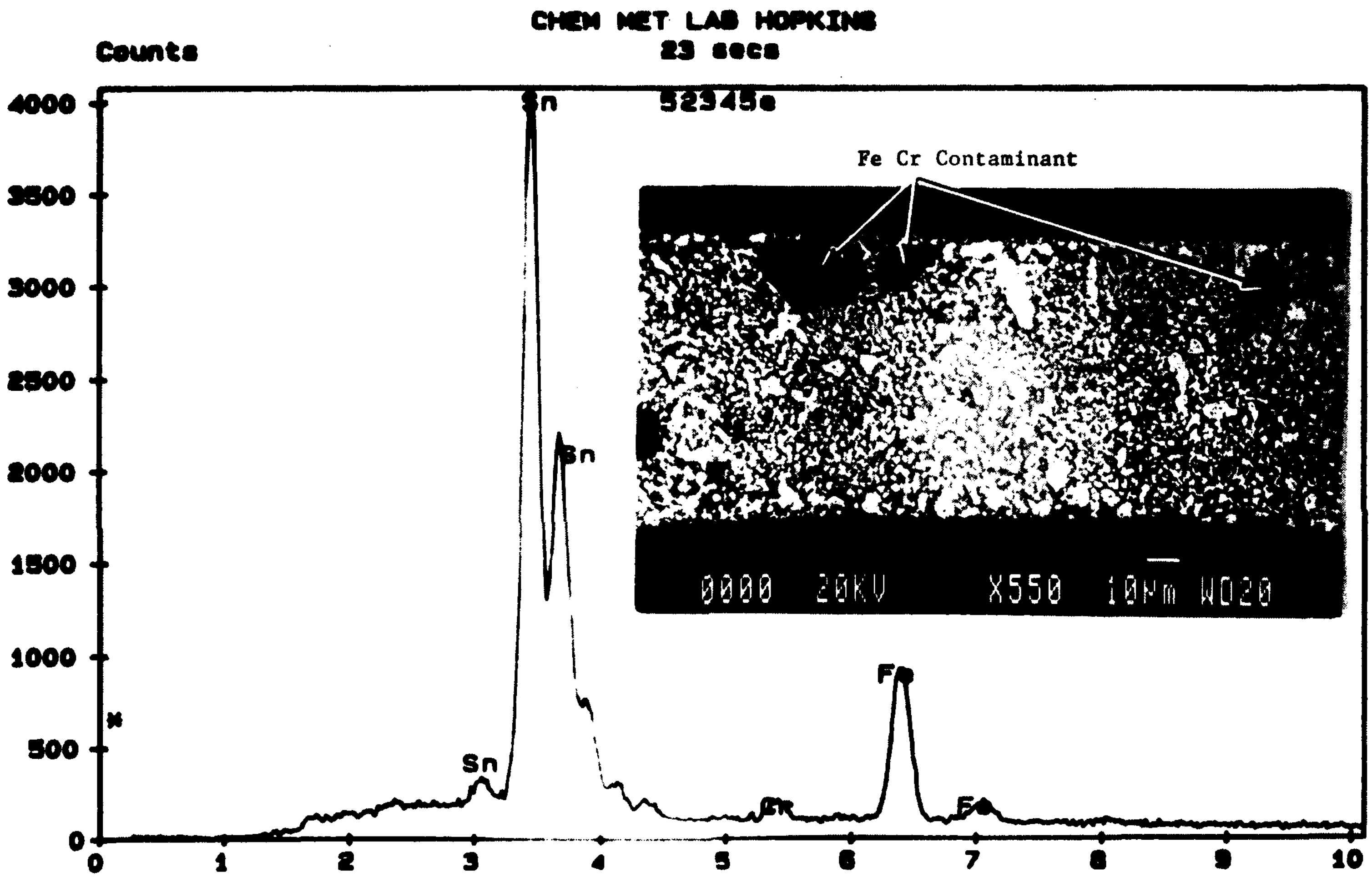


FIGURE 12. An EDS spectrum and photomicrograph of an iron and chromium contaminant typical of those found throughout specimens tinned. Magnification: 550X.

FIGURE 13. Photograph of particle of stainless steel encapsulated in solder. Magnification: 1000X.

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Voiding Mechanisms in SMT

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Abstract

The mechanisms for void formation are investigated for applications involving solder paste in SMT. Generally the voids are caused by the outgassing of entrapped flux in the sandwiched solder during reflow. The voiding is mainly dictated by the solderability of metallization, and increases with decreasing solderability of metallization, decreasing flux activity, increasing metal load of powder, and increasing coverage area under the lead of the joint. Decrease in the solder powder particle size shows only a slightly negative effect toward voiding. The data indicate that voiding is also a function of the timing between the coalescing of solder powder and the elimination of immobile metallization oxide. The sooner the paste coalescing occurs, the worse the voiding will be. Increase in voiding usually is accompanied by an increasing fraction of large voids, suggesting factors causing voiding will have an even greater impact on the joint reliability than what shown by the total-void-volume analysis results. Preliminary data show that certain predry treatment and flux solvent with higher boiling point appear to cause increased voiding.

INTRODUCTION

With the rapid advancement toward ultra-fine pitch technology, the solder joint dimension in SMT shrinks quickly as well. Since less and less solder material is allowed for each solder joint, the reliability of the joint becomes more and more of a concern. In the past, industry has concentrated the effort on the understanding and development of the criteria for selection of solder materials, optimum pad/lead design and solder joint configurations, flux corrosivity levels, solderability of metallizations, etc. However, in the case of voiding phenomenon, although being one of the most critical factors on governing solder joint reliability, the understanding level still remains speculative and very little work has been reported on this subject. Voiding is a phenomenon commonly associated with solder joints. This is especially true when reflowing a solder paste in the SMT application, as exemplified by Figure 1. Presence of voids will affect the mechanical properties of joints [1] and deteriorate the strength, ductility, creep and fatigue life [2, 3], due to the growth in voids which could coalesce to form ductile cracks and consequently lead to failure. The deterioration could also be due to the enhanced magnitude of the stresses and strains of solder caused by voids [4]. In addition, voids could also produce spot overheating [5], hence lessen the reliability of joints. It is believed [6] that, in general, voiding could be attributed to (1) solder shrinkage during solidification, (2) laminate outgassing during soldering the plated through-holes, and (3)

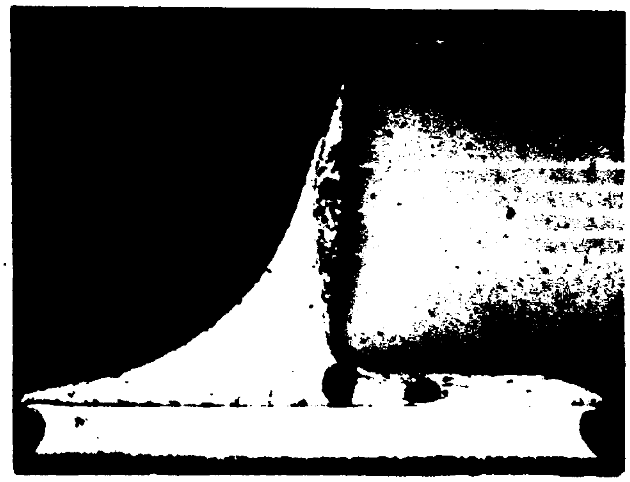

Figure 1 Voids in SMT solder joint (100X)

entrapped flux. In the case of solder pastes, although the entrapped flux is regarded as a possible cause, apparently the mechanisms for voiding are considerably more complicated and there is much more to be learned. In this work, the effects of materials on void formation are investigated. Furthermore, the effects of process conditions on voiding are also explored.

EXPERIMENT

I. Test Materials:

Materialwise, several parameters are examined in this paper. These include the flux activity, boiling point of flux solvent, solder powder particle size, metal load of paste, and substrate solderability. The flux activity is regulated by varying the activator content, and the substrate solderability is adjusted by controlling the conditioning time of copper coupons at 100°C.

Fluxes with varied activator content:
Four fluxes A, B, C, and D are made, with all components being equal except the activator content being 0.1, 0.4, 0.8, and 3.2% (w/w), respectively.

Fluxes with varied solvent boiling point:
Flux BH is made with all components being equal to B except the solvent. Solvent used in flux BH is the same chemical family but higher in boiling point (280°C) than that of flux B (230°C).

Solder Powders:
Three mesh ranges of Sn63 solder powders -200/+325, -325/+500, and -500 mesh are used, and are designated with codes 2, 3, and 4, respectively.

Solder Pastes:
The paste samples used in this study are represented by a combination of flux code, mesh code, and metal content (w/w). For example, B-3-90 represents flux B, -325/+500 mesh powder, and 90% metal load.

Copper Coupons:
Copper coupons of dimensions 0.50 × 0.625 × 0.020 inch are precleaned with 10% fluroboric acid followed by conditioning in a 100°C convection oven for a specified time. The coupons are then used in the void-samples preparation and also in the

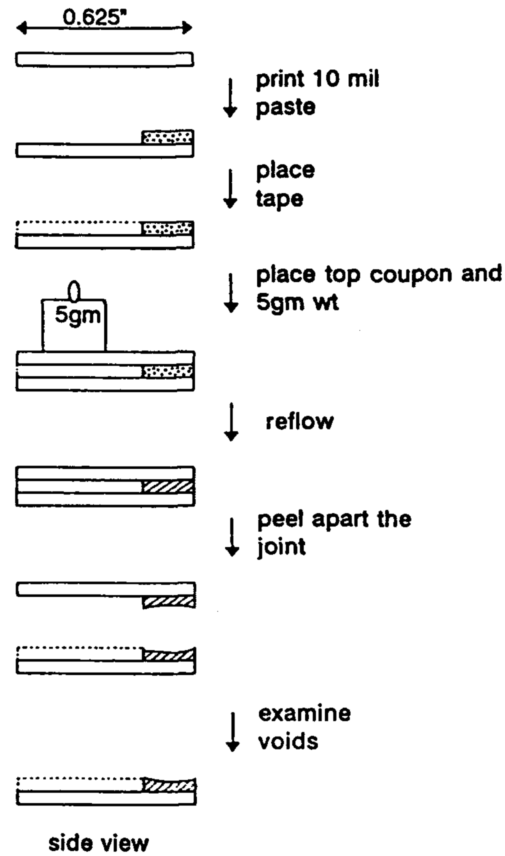

Figure 2 Void-sample test setup

wetting balance analysis.

II. Tests :

Processingwise, the paste layout and predrying effects are examined. In the case of paste layout, the paste area under coverage is modulated by varying the print width from 0.125 to 0.250 inch.

Void-Sample Test Setup :
In order to minimize the test variables, the setup of void-samples is simplified, as shown in Figure 2. Typically the paste deposited is 0.125(W) × 0.50(L) × 0.010(T) inch in dimension unless otherwise specified. A tape is used as a spacer as well as a solder resist and is approximately 0.005 inch in thickness.

Reflow Profile:
The void-samples are reflowed via a two-stage SIKAMA reflow hot plate with a profile 150°C

preheat stage (50 sec)/ 230°C reflow stage (50 sec) typically. Prior to reflow, the samples are predried in a 100°C convection oven for 20 minutes unless otherwise specified.

Wetting Balance Analysis:
The flux activity and copper coupon solderability are determined with the use of Sn63 solder bath at 210°C. In the case of flux activity effect study, the activity is determined using coupons with 3 hrs conditioning time. As to the solderability effect study, coupons with varied conditioning time are evaluated with the use of flux B. In this study, both flux activity and copper coupon solderability are defined as $\text{Log}_{10}(1/S)$, where S is "wetting time", as illustrated by Figure 3. Hence the smaller the S value, the higher the flux activity or the greater the solderability.

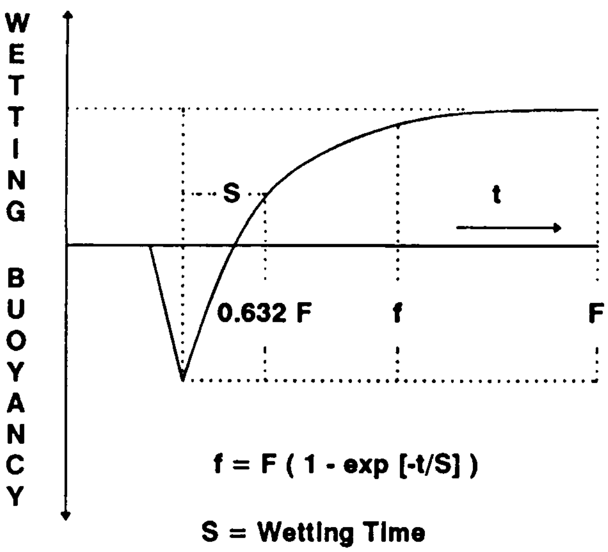

Figure 3 Kinetics of wetting

Paste Coalescing Time Determination:
The coalescing time of pastes are determined by measuring the time needed for a paste to coalesce in a typical solder ball test [7] at 180°C. The pastes used are A-2-90, B-2-90, C-2-90, and D-2-90. The average of 10 test samples is used for each paste.

Void Measurement:
After the void-sample has been peeled apart, the ruptured joint surface is examined under an optical microscope and the void diameters are determined with the use of a built-in micrometer. Figure 4 shows typical examples of large and small voids

Figure 4 Photo of large and small voids in a cross-sectioned solder joint (200X)

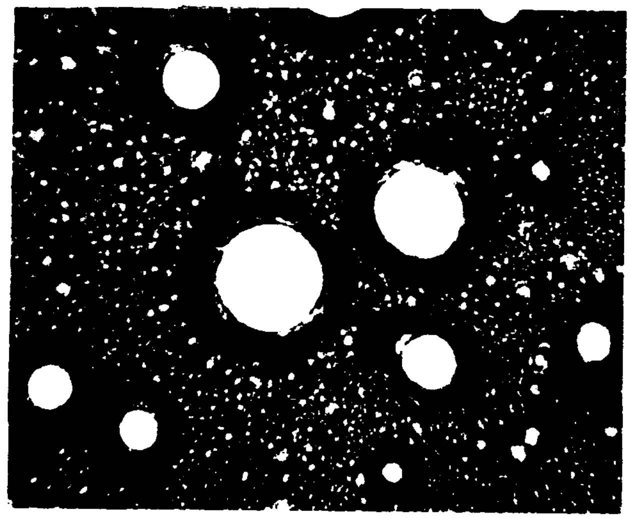

Figure 5 Photo of the joint surface after the void-sample has been peeled apart (65X)

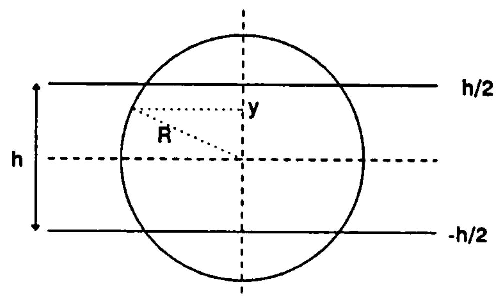

Figure 6 Model simulation of large void in void-sample for volume calculation

observed in a cross-sectioned solder joint. Figure 5 shows the joint surface after the void-sample has been peeled apart. Obviously the small voids can be treated as spheres. As to the voids with a diameter greater than the joint thickness, the void shape is approximated with a symmetrically sliced sphere,

$$\begin{aligned} V\ (\textit{void volume}) &= \int_{-h/2}^{h/2} \pi\left(\sqrt{R^2-y^2}\right)^2 dy \\ &= \pi R^2 h - \pi \frac{h^3}{12} \quad \ldots\ldots\ldots\ eq(1) \end{aligned}$$

where h = *joint thickness*
R = *void radius*

as shown in Figure 6. The void volume of such shape is calculated using equation (1). For each set of testing parameters, the void volume percentage of joint volume is calculated from the average of 10 test samples.

RESULTS

I. Effect of Flux Activity:

At first, the effect of flux activity on voiding is examined. The flux activity is regulated by varying the activator content (see Figure 7).

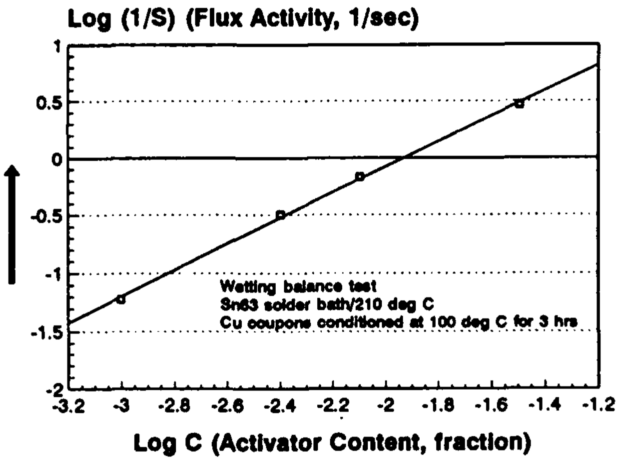

Figure 7 Relation between flux activity and activator content

Four pastes are used in this study, consisting of fluxes A, B, C, and D and 90% Sn63 (-200/+325 mesh). The void content of those four pastes are determined with the samples being predried at 100°C for 20 minutes prior to reflow. By examining the void appearance under the optical microscope after the void-samples are peeled apart, it is firstly noticed that most of the voids show no entrapped organic residues, and only very few voids exhibit a noticeable amount of residue. This indicates that most of the voids are formed due to the outgassing of fluxes or fluxing reactions, and therefore upon cooling the vapor condenses and leaves no sign of

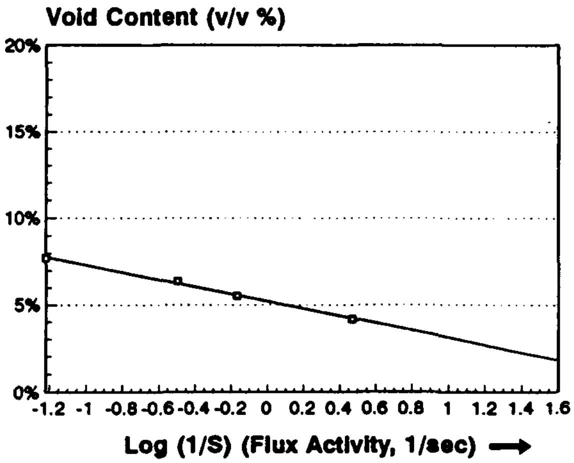

Figure 8 Effect of flux activity on voiding

residues. The measurement results indicate that the void content decreases with increasing flux activity (see Figure 8). Since higher flux activity supposedly will generate more fluxing reaction products, the lower void content associated with higher fluxing activity suggests that fluxing reaction or activator and activator-induced decomposition are not the major sources of outgassing. In other words, the outgassing of entrapped flux is directly responsible for the major void formation, and a lower void content means a lesser amount of entrapped flux. When using a solder paste, the flux is in direct contact with the surface oxide of powders and surface-to-be-soldered. Hence at reflow any residual oxide can be expected to be accompanied with some flux adhered. Considering that a higher activity flux usually eliminates the oxide more rapidly and completely, therefore leaves fewer spots for the flux to adhere to, the relation observed in Figure 8 becomes easily comprehensible.

II. Effect of Substrate Solderability:

To investigate the effect of substrate solderability on voiding, a similar test is conducted on a series of copper coupons which have been conditioned at 100°C for various periods of time in order to regulate the thickness of copper oxide. The solderability of those coupons are determined with the use of flux B, as shown in Figure 9. Naturally, as the conditioning time increases, the solderability of the copper coupon decreases. The relation between the void content and the solderability of copper coupons is shown in Figure 10. Apparently, the void content decreases with increasing

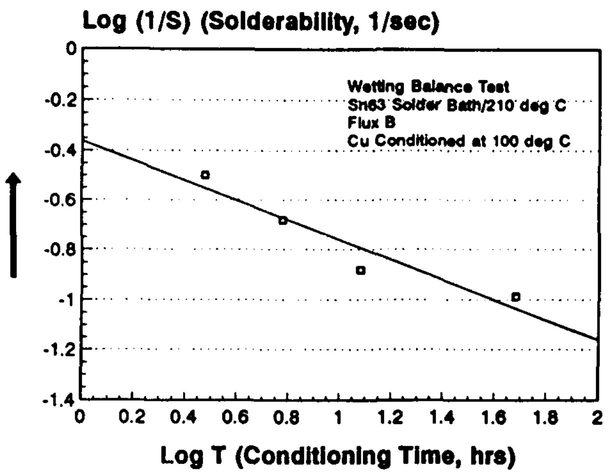

Figure 9 Relation between conditioning time and solderability

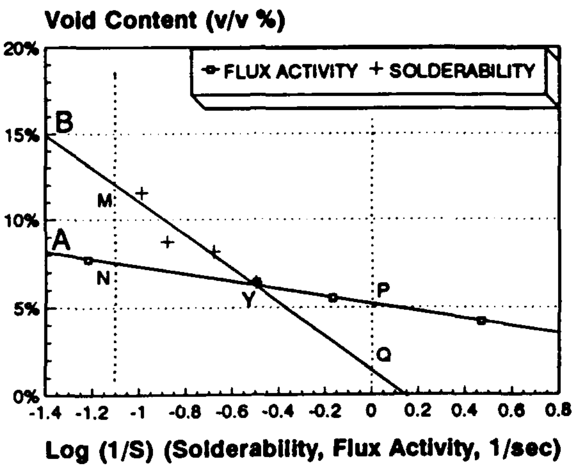

Figure 11 Relative impact of solderability and flux activity on voiding

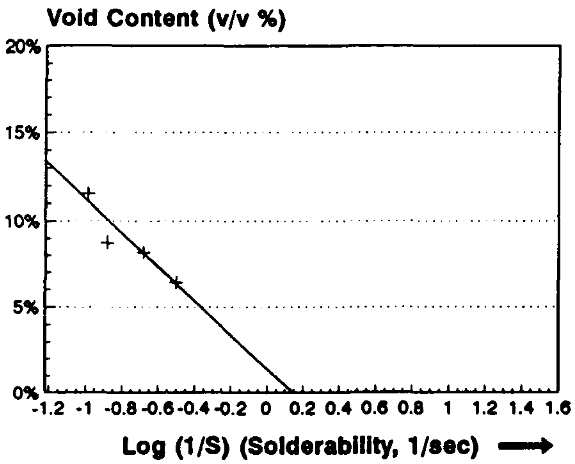

Figure 10 Effect of solderability on voiding

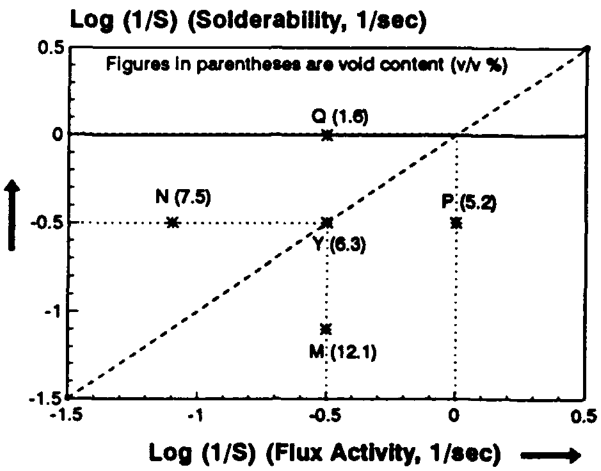

Figure 12 Wetting time background for flux activity and solderability determination

solderability. This can be explained by the same mechanism discussed above. With increasing solderability, the substrate oxide can be cleaned more readily, hence allows less opportunity for the flux to be entrapped to form voids.

III. Timing Factor:

In sections I and II of RESULTS, it has been shown that the voiding is inversely proportional to the flux activity and solderability. Per the definition, both flux activity and solderability are equal to $Log_{10}(1/S)$. In other words, the voiding is proportional to the wetting time S. However, when the two relationships are analyzed together, as shown in Figure 11, it is interesting to note that the voiding phenomenon is not a sole function of wetting time, and obviously is more sensitive to the solderability of the substrate (curve B) than to the flux activity (curve A). The difference in sensitivity can be well exemplified by comparing the points P vs Q, and M vs N. Figure 12 provides the wetting time background information for those points. Before examining the data, it should be kept in mind that all the solderability data are generated with the use of flux B (flux activity = -0.5), and all the flux activity data are generated with the use of copper coupons conditioned for three hours (solderability = -0.5).

By comparing Point P and Point Q of Figure 12, although both points exhibit the same wetting time

S ($\log_{10}(1/S) = 0$), P has a higher flux activity but a lower solderability than Q. A higher flux activity suggests a lower voiding, while a lower solderability suggests a higher voiding. Since P shows a higher voiding (5.2%) than Q (1.6%), it becomes evident that the voiding trend is governed by the solderability factor. The same conclusion can be arrived at by comparing Point M and Point N. This discriminating sensitivity possibly can be attributed to a "timing factor". For instance, Point P and Point Q display the same wetting time for the copper substrate. This means the elimination of copper oxide by flux occurs at the same rate. However, since Point P utilizes a flux with higher activity than Point Q, the paste of Point P is believed to coalesce sooner at reflow. Accordingly, at Point P less time will be allowed for the flux adhered to the substrate oxide surface (an immobile phase) to escape. In addition, even if the substrate oxide can be cleaned by the flux after it has been entrapped in the molten solder, according to Stoke's law it is very difficult for the flux to escape [8]. Consequently the entrapped flux will serve as an outgassing source and constantly release vapor which directly contributes to the void formation.
To verify this hypothesis, the coalescing time of pastes with various activator contents is determined at 180°C, with results shown in Figure 13. Generally speaking, the coalescing time of pastes indeed decreases with increasing flux activator content (or flux activity). Hence it can be concluded that voiding is also a function of the timing between paste coalescing and elimination of the immobile metallization oxide. The sooner the paste coalescence occurs, the worse the voiding will be.

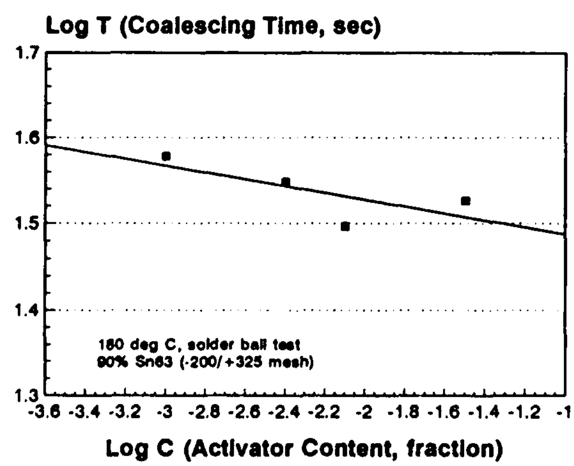

Figure 13 Coalescing time of pastes with various activator contents

IV. Void Size Distribution:

Although it has been reported that porosity does not affect the reliability of the soldered joints [9], at least large voids are generally considered unacceptable by industry. Therefore, in the investigation of voiding mechanisms, it is essential to know the effects of voiding factors not only on the total void content but also on the void size distribution. In this work, the void size distributions are analyzed together with the void content evaluation as a function of voiding factors. In general, the number fraction of voids decreases rapidly with increasing void diameter. This is true in spite of the total void content, as exemplified by Figure 14 (0.8% activator, 5.6% total void content) and Figure 15 (0.1% activator, 7.8% total void

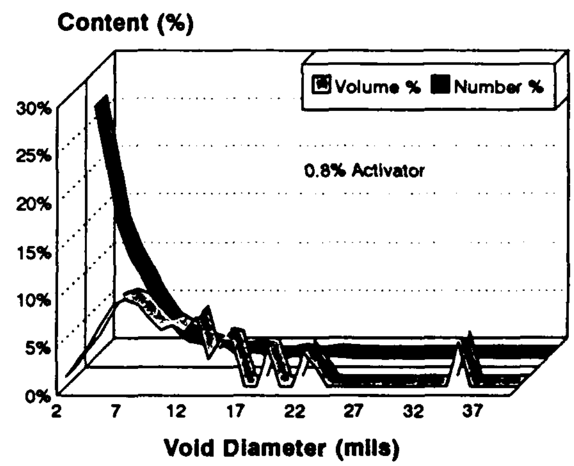

Figure 14 Void size distribution of C-2-90

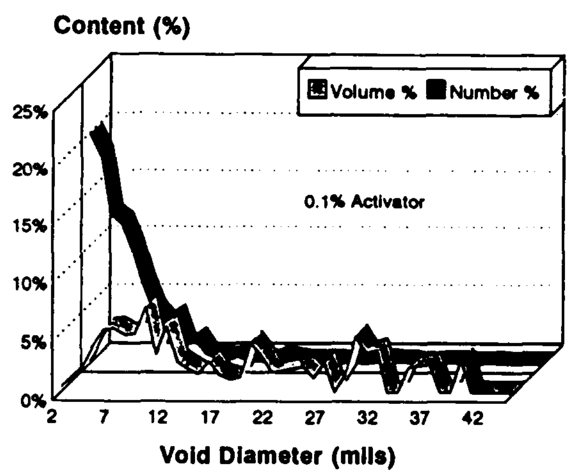

Figure 15 Void size distribution of A-2-90

content). The volume fraction of voids vs void diameter relations appear to be more complicated. However, by examining the relations between the accumulated volume fraction of voids and void diameter (see Figure 16), it becomes obvious that while the void content increases with decreasing flux activity (see Figure 8), so does the fraction of large voids.

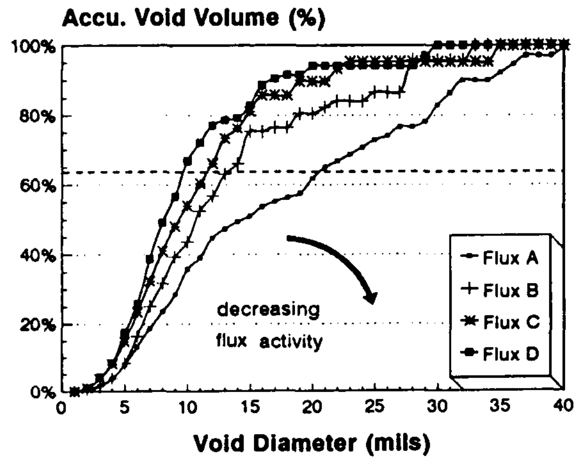

Figure 16 Effect of flux activity on void size distribution

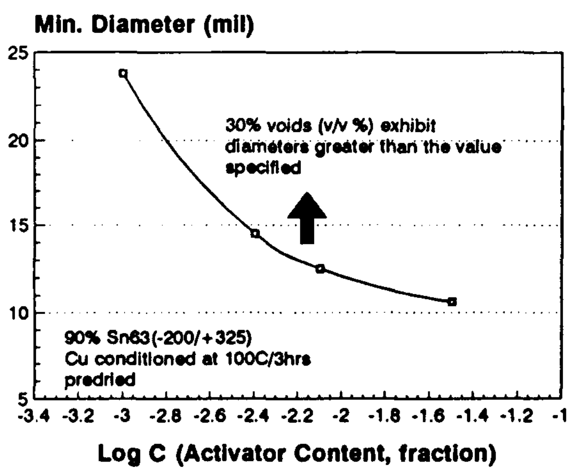

Figure 17 Effect of flux activity on the tendency of forming large voids

Furthermore, the increasing rate of large voids fraction ramps up rapidly with decreasing flux activity, as shown in Figure 17. Similar relationships are also observed on other voiding factors, such as solderability. Therefore it can be summarized that the volume fraction of large voids increases with increasing void content as a result of voiding factor adjustment. Since it is reasonable to speculate that large voids are more harmful than small voids, the results here suggest that factors which cause voiding will have even a greater impact on the solder joints reliability than what shown by the data of total-void-volume analysis.

V. Effect of Coverage Area:

The coverage area of paste is expected to be another crucial factor for voiding. Its effect is studied by varying the print width of paste B-3-90, with the results shown in Figure 18. Apparently the voiding decreases with decreasing coverage area. Since the print thickness and the final joint height remain constant, reduction in print width means an increase in the ratio of side-opening to total solder volume, and consequently facilitates outgassing and entrapped flux to escape. With the advancement of ultra-fine pitch technology, the coverage area is expected to be smaller and smaller. This suggests that, on the issue of voiding, the coverage area factor is favoring the shift toward ultra-fine pitch technology.

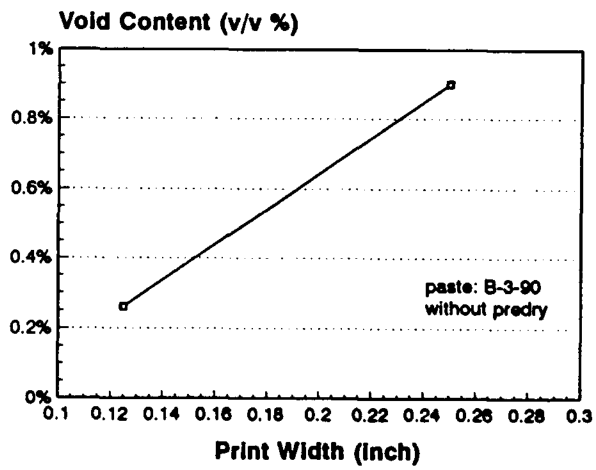

Figure 18 Effect of paste coverage area on voiding of paste B-3-90

VI. Effect of Metal Load:

Two series of pastes, B-2 and B-3, are used, with metal load ranges from 85% to 92% in both cases. The samples are processed without predrying. In general, both series show an increase in voiding when the metal load increases (see Figure 19). This can be attributed to (1) an increase in total solder powder oxide, (2) a decrease in flux content for copper oxide removal, and (3) possibly a greater difficulty for flux to escape due to a tighter powder

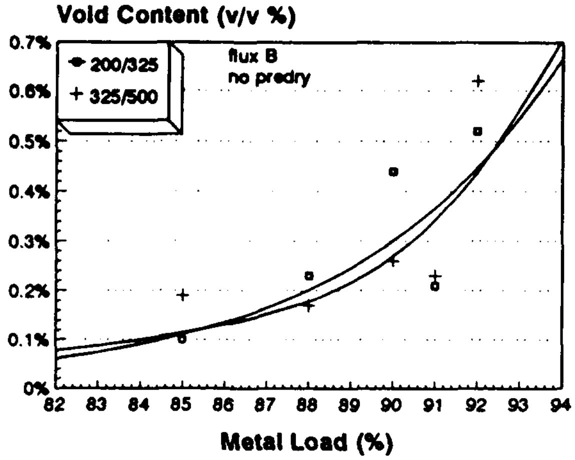

Figure 19 Effects of metal load and powder size on voiding

packing. The increase in solder oxide not only reduces the flux quantity needed for cleaning substrate oxide, but also increases the chances of leaving some trace of solder oxide entrapped in the molten solder during reflow. However, the effect of this factor should not be overemphasized, as will be discussed in the next section.

VII. Effect of Powder Size:

By examining Figure 19, it is found that powder size seems to have a negligible effect on voiding. To further verify this, one more paste sample B-4-90 (-500 mesh) is also tested, with the void content being 0.41%. This value is only slightly higher than the value 0.26% of paste B-3-90 (-325/+500 mesh), suggesting that decreasing the powder size only causes a slight increase on voiding. Being a mobile phase, any residual solder oxide probably can be segregated relatively easily from the interior of molten solder. This may explain, at least partially, why the powder size effect is much milder than that of immobile substrate oxide.

Sample	Predry	Void Content (v/v %)
B-2-90	Yes	6.40
B-2-90	No	0.44
B-3-90	No	0.26
BH-3-90	No	1.01

Table I Effects of predrying and solvent boiling point on voiding

VIII. Effects of Predrying/Solvent Boiling Point:

The results (Table 1) show that predrying at 100°C for 20 minutes causes a significant increase in voiding. Presumably this can be attributed to further oxidation which occurs during predrying. In Table 1, the effect of solvent boiling point is also explored. The data suggest that fluxes with a high boiling point solvent seem to aggravate voiding slightly, probably due to the outgassing of the residual solvent in the entrapped flux.

DISCUSSION

I. Void Volume Assessment:

The void volume is determined by measuring the diameter of voids exposed on the peeled joint surface. Some voids with a diameter smaller than the joint thickness may be buried in the solder therefore are not measured. Voids of such type are estimated to be no larger than 0.004 inch in diameter. In addition, voids with diameter smaller than 0.001 inch are not determined, due to the limitation of instrumentation. However, errors caused by those two sources on the void volume content determination are very small and are estimated to be no more than 5% (see Figure 16).

II. Effects of Predrying and Solvent Boiling Point:

The preliminary results in this work suggest that a certain predry treatment and a certain higher boiling point solvent cause an increase on voiding. However, this should not be regarded as a general rule. Since the outgassing rate is expected to be a function of both the amount of residual solvent in the entrapped flux and the vapor pressure of this solvent, it is reasonable to believe that the optimum predry/reflow process should really be a function of solvent vapor pressure. Besides, the possibility of further oxidation during heating treatment needs to be considered also.

III. Control of Voiding:

Solder Paste Material:
To reduce the voiding, using fluxes with higher fluxing activity appears to be a very crucial approach. Use of solder powders with a low oxide content is another valid approach. Other approaches, such as lower metal load and coarser powder, are also helpful. However, current trends indicate that, in general, a higher metal load and

a finer solder powder are favored for advancement of ultra-fine pitch technology. This implies that the last two approaches stated above will have only very limited usage.

Component/Substrate Metallization:
Improvement of the solderability of component leads and substrate pads is considered the most important way of reducing voids. Although, in general, the poor solderability of metallization can be compensated somewhat with the use of a stronger flux, the improvement on voiding is expected to be limited due to the "timing factor". As discussed above, a stronger flux usually results in a shorter time for paste to coalesce. When the paste coalesces sooner than the substrate oxide removal, a higher chance of entrapping some flux in the solder will be resulted in.

Heating Process:
Since outgassing of flux has been identified as the cause of voiding, theoretically drying should help to reduce voiding. However, in many instances adjusting heating processes (including predry and reflow profile) appears to give unpredicted results. Presumably this can be attributed to the interference of oxidation, and can be corrected by using an inert heating atmosphere. As to the "timing factor", a slow heating profile with a long preheat stage is expected to promote cleaning of immobile metallization oxide prior to paste coalescence, and accordingly reduces the possibility of entrapping the flux in the solder.

CONCLUSIONS

The voiding mechanisms are investigated for applications involving solder paste in SMT. Generally the voids are caused by the outgassing of entrapped flux in the sandwiched solder during reflow. The voiding is mainly dictated by the solderability of metallization, and increases with decreasing solderability of metallization, decreasing flux activity, increasing metal load of powder, and increasing coverage area under the lead of the joint. Decrease in solder particle size causes only a slight increase on voiding. Voiding is also a function of the timing between the coalescing of solder powder and the elimination of immobile metallization oxide. The sooner the paste coalescing occurs, the worse the voiding will be. Increase in voiding usually is accompanied by an increasing fraction of large voids, suggesting factors causing voiding will have an even greater impact on the joint reliability than what shown by the total-void-volume analysis results. Control of voiding may include (1) improving component/substrate solderability, (2) using fluxes with higher flux activity, (3) reducing solder powder oxide, (4) using inert heating atmosphere, and (5) slowing down the preheat stage to promote fluxing before reflow.

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INFRARED TECHNOLOGY COUPLED WITH R.F. INDUCTION SOLDERING A QUANTIFIABLE LOOK AT PROCESS CONTROL SUCCESS

by

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ABSTRACT

Through the coupling of infrared sensing technologies and automated R.F. induction soldering equipment, the process controls necessary to ensure compliance with MIL-STD 2000 relative to soldering time requirements and corrective action implementation and monitoring, are both measurable and repeatable. This process includes the ability to reduce operator dependency as well as produce permanent, hard copy data. This data can be maintained as individual solder joint "fingerprints" for manufacturing records and failure analysis / corrective action. An additional benefit of the process is the ability to ensure that temperature sensitive areas of a given assembly or package are not exposed to unintentional collateral heat, thereby reducing or eliminating thermal damage to adjacent components or materials. The system allows for immediate adjustment of time and temperature parameters and lends itself to multipin applications. The equipment is bench mounted and relatively portable. The system can be adapted simply and inexpensively to multiple applications.

THE SYSTEM

The I.R. 6000 is comprised of four major components; the R.F. Induction Soldering Unit, the Infrared Detector (or head), the Thermal Monitor and the Graphic Plotter.

The R.F. Induction Soldering Unit utilized for the system is the Seven Associates model B-1A Portable Induction Heating Unit. It is designed with an internal transformer arrangement which enables the utilization of a multiplicity of single turn concentrators which are attached directly to the output. There is no shock hazard as the unit is electrically grounded internally. It is basically an R.F. generator which supplies a high AC voltage to the primary of an R.F. transformer. The voltage is then stepped down to a very low voltage, high current, in the secondary. This high density

EXPLANATION OF THE PROCESS AT WORK

One of the first considerations to be taken into account when utilizing R.F. induction soldering is the location of the material to be soldered in conjunction with the concentrator. Once the location is defined, a fixed tool or holding fixture will eliminate this variable from the soldering process. A good rule of thumb for initial engineering of the process is to concentrate the power where solder flow is ultimately desired. Solder will flow to the heat.

The next step in the process is to define temperature settings for the Thermal Monitor. The preferred way of doing this is referred to as the Band Control Method. The Band Control Method allows the part to come up to a given temperature and then cycle between two temperature settings for a pre-determined period of time. As previously referenced, once the solder is in the eutectic stage it should not remain molten for more than five seconds (It should be noted that the temperature of the solder in its eutectic state can be higher than its melting point). When soldering with this method, the R.F. induction unit will turn off at the "high" parameter and "on" at the low parameter for the period of time established and set on the Thermal Monitor. Actual temperature and time settings will vary with the mass of the materials to be soldered. It is important to ensure that the "power" setting on the R.F. induction unit be maintained at a point where the unit is not ramping up so fast as to overshoot the previously defined temperature limit.

An alternate method of setting/utilizing the system when cycling is not necessary may also be used. In this case the timer on the Thermal Monitor which typically controls the "low" setting is set to allow the temperature profile to not exceed the "high" limit. The "high" setting can then be used as a "not to exceed" temperature. the R.F. induction unit when controlled in this manner will heat the materials in the concentrator until the "low" timer set point is reached. At this juncture the timer becomes activated for the set period and during this time the system will not allow the "high" temperature setting to be exceeded.

The final step prior to the actual soldering operation is the "aiming" of the Infrared Detector. With the fiber - optic light source energized, the beam is located at the intersection of the materials to be soldered and the solder rings. During a preliminary set-up a test vehicle would be located in the concentrator and the solder rings flowed with

an initial emmisivity setting indicated on the Thermal Monitor. The liquidus state of various solder types has been well researched and documented. The operator should observe when the solder begins to melt. As the solder melts, the known melting temperature of that particular solder type should register, within a degree or two, on the digital readout of the Thermal Monitor. If the correlation is off by more than two degrees, the emmisivity setting should be adjusted slightly to fine tune the temperature reading. It is necessary to ensure that the "low" and "high" limits be set higher than the melting point of the solder in order to avoid cycling precisely at the liquidus point. Additionally, once the light source has verified the aiming of the Infrared Detector, it must be turned off prior to the soldering operation as the light can affect the Thermal Monitor temperature readings.

There are other methods available for setting the emmisivity. These include matching thermocouple measurements, coating an area on the material to be soldered with high temperature black paint for use as a "control" from which adjustments may be made or the use of an Emmisivity Table from an Engineering Handbook or any other reliable source.

The two above referenced methods of utilizing the system provide the controls necessary to monitor the process at a level which is genuinely discrete. The use of solder rings (or preforms) enhances this discretion and generates even more process control. Both of these methods have their own benefits, depending on the task for which they are applied. The Band Control Method is best suited for the requirements of Mil-Std 2000 in that the temperature can be maintained at + / - 5 degrees fahrenheit for the 2 to 5 second time duration. The alternate method is best applied to tasks requiring the ability to process a solder joint without inducing thermal stress or damage to surrounding components. An example of this usage would be the soldering of a microwave package. Rather than aiming the fiber - optic light source at the area to be soldered, it would be aimed at or near the the critical area. The system will ensure that the preset "high" temperature will not be exceeded. The hard copy data in this case would then provide the user with a temperature profile of the heat sensitive area during the adjacent soldering operation.

Once all the pertinent parameters have been arrived at and qualified, a simple work instruction detailing the settings required to solder a particular assembly are all

that is needed for an operator to produce reliable, repeatable solder joints. Set-up time takes only minutes and the tasks the operator performs necessitate little or no training.

System calibration can be accomplished quickly and easily utilizing a "Black Body" source calibrator supplied with the system.

The data produced from the recording of a Band Control Method soldering operation is shown in FIGURE 1. The chart recording displays the "fingerprints" of three solder joints generated from a single set of parameters programmed into the I.R.6000. The comparitive results between the solder joints are very uniform. The chart recording delineates solder temperature highs and lows. The annotation of dwell time (as recorded from the timer on the Thermal Monitor) completes the record.

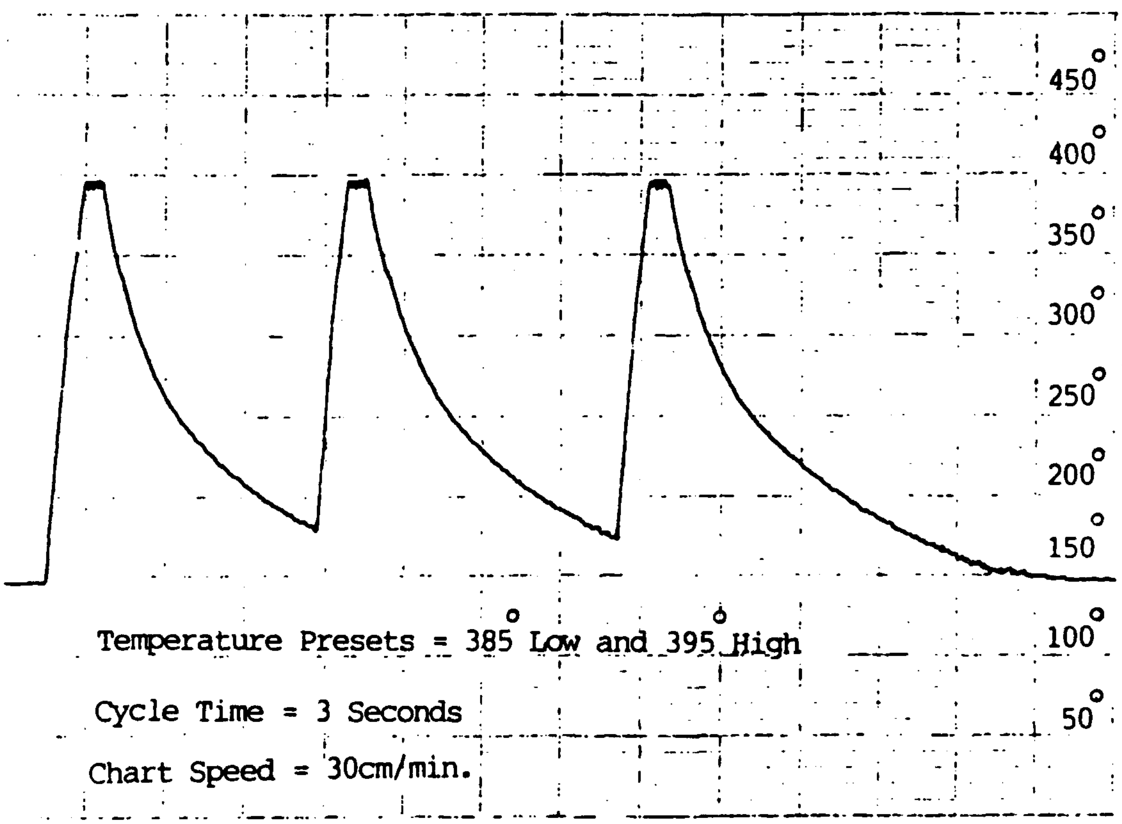

FIGURE 1. "Fingerprint" Record of 3 Solder Joints Processed Using the Band Control Method.

FIGURE 2 depicts the data produced by the I.R. 6000 during processing utilizing the alternate method to produce a solder joint. This method is also consistently repeatable.

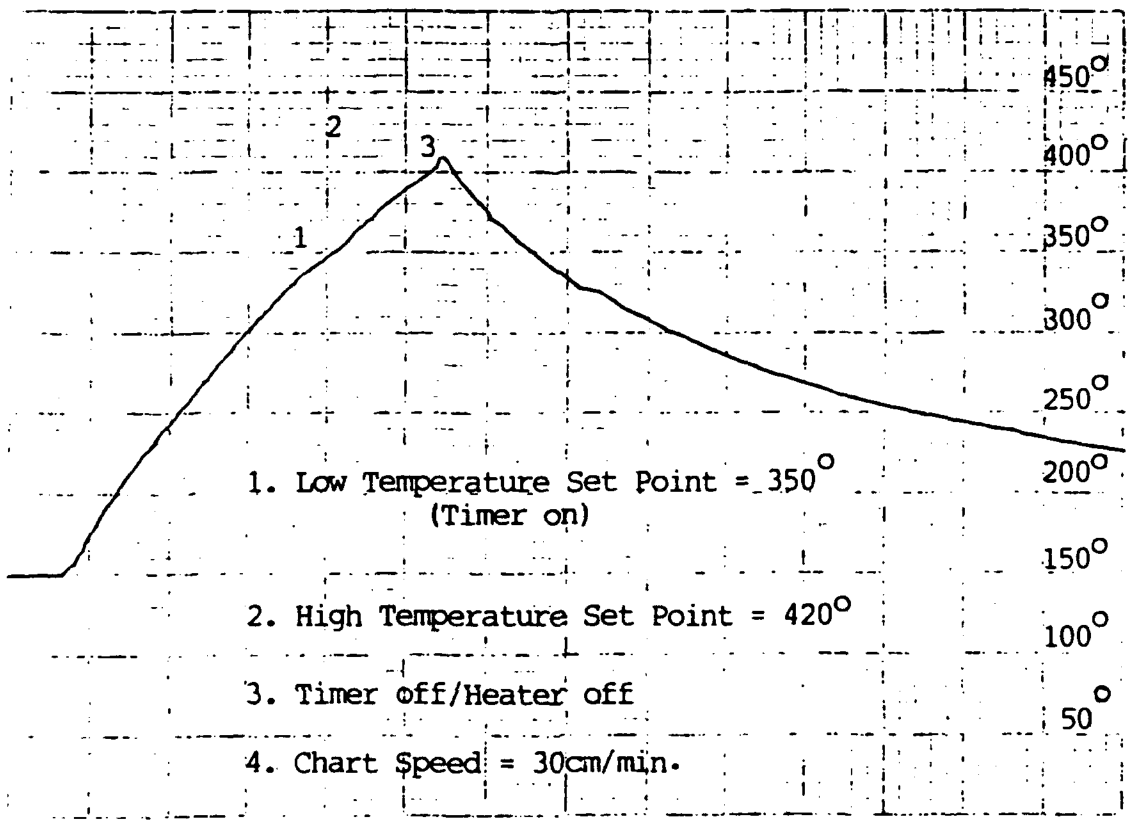

FIGURE 2. "Fingerprint" Record of a Solder Joint Processed Using the Alternate Method.

APPLICATIONS

The I.R. 6000 can be utilized for practically any soldering operation that is normally performed by Soldering Iron, Vapor Phase System, Heat Gun or Resistance Soldering (Tweezers). While there are always special instances where one method of operation is preferable to another (even though one is more difficult or cumbersome), the consideration of quantifying an operation should not be discounted.

The following list is a representative sampling of applications for the system:

1. CONNECTOR TERMINATIONS
2. SHIELD TERMINATIONS
3. PIN/SOCKET TERMINATIONS
4. MICROWAVE WAVEGUIDES
5. ORGANIZED WIRING SYSTEMS
6. SOLID STATE PACKAGES
7. HERMETIC SEALING

WHAT CAN BE GAINED BY THE USE OF THE TECHNOLOGY ?

From a quality and reliability standpoint, the system is an excellent tool for understanding and stabilizing the soldering portion of the manufacturing process. A more integral knowledge of the cause and effect of process changes enables the cognizant engineer to affect meaningful and verifiable improvements. Through the discrete adjustments that are initiated from the study of previous input parameters, the soldering operation becomes fine tuned. In cases where the system is used for the purpose of monitoring or limiting temperature profiles of non-soldered areas, the benefits of the system remain the same.

Hard copy data is generated and can be maintained for either Engineering Studies or for Quality Assurance Records. Comparitive workmanship standards can be formulated and utilized both at the workstation and by Quality Control.

By defining, quantifying, and controlling the soldering operation, individual "techniques" of different operators are eliminated. An individual with little or no understanding of the process is capable of producing consistently acceptable workmanship. The results of which can be independently verified.

In terms of the process control/continuous process improvement requirements of doing business in todays global economy, any manufacturing operation that can be better defined and more discretely controlled, should be implemented. Ultimately, the I.R.6000 system is a quantifiable process which can be documented and followed with little or no deviation. The system can be easily modified when necessary, in the event of aesthetic or material requirement changes.

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RECENT ADVANCES IN SEMI-AQUEOUS CLEANING

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ABSTRACT

Many printed wiring board assemblers and metal fabricators are investigating new cleaning agents and technologies to replace CFCs. Semi-aqueous cleaning is a good alternative because it provides superior performance and ecological advantages over CFC-113/methanol and aqueous cleaning technology.

In the semi-aqueous process, printed wiring board assemblies are cleaned in an organic solvent. The cleaning solvent is then rinsed from the parts with water. The solvent is insoluble in water, and the vast majority of the solvent can be separated from the water by decantation. Rinse water, with the small amount of remaining organic material can usually be *discharged to a POTW*. However, many users prefer to recycle the rinse water. Closed-loop technology based on membrane separation techniques is particularly suited for treating rinse water effluent from semi-aqueous installations.Data from Du Pont's membrane technology development program are presented in this paper.

INTRODUCTION

Chlorofluorocarbons (CFCs) and certain chlorocarbons such as 1,1,1-trichloroethane will not be used for cleaning circuit assemblies in the near future. They will be phased out, according to the terms of the Montreal Protocol, to protect the delicate ozone layer in the earth's upper atmosphere. The elimination of CFC-based products and some chlorocarbons, once considered ideal cleaning agents, is forcing assemblers to seek alternative cleaning technologies.

Manufacturers are implementing "no-clean" processes, aqueous cleaning techniques, and semi-aqueous cleaning technology to replace CFCs and 1,1,1-trichloroethane. Although the "no-clean" alternative is an attractive one, it is not a panacea. Many manufacturers can not easily eliminate cleaning. Aqueous cleaning is useful for some applications. Because aqueous cleaners are often acidic or basic and can dissolve metals and metal oxides, they create expensive waste treatment problems.

Semi-aqueous cleaning technology is emerging as the most attractive alternative. Semi-aqueous cleaners offer zero ozone depletion potential (ODP), provide excellent cleaning[1,2], and significant ecological advantages over aqueous cleaning technology[3]. They are not acidic or basic; therefore, they are less likely to dissolve metals. The semi-aqueous process, by design, allows for segregation and isolation of soil and the cleaning solvent from the rinse water stream. One key advantage for printed circuit assemblers is that they do not have to alter their soldering processes to use semi-aqueous cleaning technology. The semi-aqueous process was designed to clean synthetic and rosin-based fluxes and solder pastes.

In a typical semi-aqueous cleaning machine, soils on parts are dissolved in the organic solvent in the solvent chamber. The contaminated organic solvent is removed from the parts by a series of water rinses.

A two-step method is used to remove the organics from rinse water. Most of the removal is done in the first rinse stage, also called the emulsion rinse. The second step is a membrane system to purify water from the second and third rinse stages.

This paper will focus on a low volatility semi-aqueous solvent, the effect of solvent choice and equipment design on VOC losses, and the membrane technology used to purify water from the final rise stages.

SEMI-AQUEOUS CLEANING AND VOLATILE ORGANIC COMPOUND (VOC) EMISSIONS

The latest semi-aqueous cleaner for electronics defluxing from Du Pont is a combination of polar and non-polar hydrocarbons with a non-ionic surfactant. This cleaner has recently been judged "better than " the benchmark CFC 113/ methanol azeotrope for defluxing in a Phase 2 test in the Cleaning and Cleanliness Test Program sponsored by the EPA/DoD/IPC Ad Hoc Solvents Working Group. The cleaning data from this test are contained in Table 1.

Table 1. Phase 2 Test Results

	PHASE 1 CFC-113/MEOH AZEOTROPE	PHASE 2 AXAREL® 32
IONICS(μgr NaCl eq./in^2	10.7	3.3
RESIDUAL ROSIN(μgr/board)	3,945	693

Because this formulation has a very low vapor pressure (less than 0.1 mm Hg.), VOC emissions from a cleaning process using this solvent are minimized. This is becoming an important factor in selection of a cleaning agent because some local VOC regulations now require a VOC permit review if a new process emits more than 1 pound/day of VOC additionally. In-line semi-aqueous cleaning systems using low vapor pressure solvents typically lose 0.7-1.0 lbs./hr, principally from the solvent and first rinse stages. However, it is common for an in-line cleaning system using a CFC/alcohol azeotrope or blend to emit VOC's in a similar range. Therefore, switching from a CFC/alcohol solvent process to a semi-aqueous solvent process may not result in appreciably higher VOC emissions.

In addition to choosing a low vapor pressure solvent, the following measures can be taken to minimize VOC losses:

- -Minimize temperature in the solvent and first rinse sections of the cleaning process, consistent with good cleaning results
- -Minimize air contact in the solvent and first rinse sections
- -Minimize ventilation flow rates
- -Minimize droplet entrainment with baffles or demisters
- -Optimize air knives to prevent mist formation
- -Consider vent scrubbers or condensers. Calculations indicate that up to 50% of VOC losses cound be removed with condenser temperatures in the 35-40°F range.

THE SEMI-AQUEOUS CLEANING PROCESS: EMULSION RINSE

Figure 1 is a schematic drawing of an advanced semi-aqueous cleaning machine. The tank on the far left is the solvent tank and contains pure Axarel® cleaning agent. In this tank, soils are dislodged and/or dissolved in the solvent. Agitation and heat can be applied to minimize the cleaning time. Over

time, the concentration of soil in the cleaning solvent will increase. The amount of solvent carried into the following stage, dragout, can be controlled by adjusting the air knives, so that the soil concentration reaches the desired equilibrium level. For example, if a board has 1 gram of flux residue on it as it enters the solvent module, and drags 10 grams of conta.. inated solvent into the emulsion tank, the equilibrium flux concentration in the solvent stage will be 10%. One current installation, operating two high-volume in-line machines has achieved equilibrium concentrations of 11% & 15%. The solvent bathes have not been replaced for 11 months.

The parts next travel to the first rinse tank where they are given a preliminary rinse with an aqueous emulsion that contains a relatively high concentration of semi-aqueous cleaning agent. This emulsion rinse is not discarded to drain but is instead periodically discharged to a decanter. In the relatively quiescent decanter, the emulsion separates into an aqueous layer and an organic layer. The organic layer, which is comprised of the semi-aqueous cleaning agent and the soil, is decanted. This "dirty" solvent can be used as a fuel. The aqueous layer is returned directly to the emulsion section of the machine and reused without purification.

When parts exit the first rinse section of the cleaning machine, they are covered with a small amount of emulsion. If a part is coated with 10 grams of an emulsion which is 10% semi-aqueous cleaning agent and 90% water, one gram of organic material will be carried into the subsequent rinse sections of the cleaning machine. If the emulsion is only 3% semi-aqueous cleaning agent, 0.3 grams of organic material will be carried into the rinse sections of the machine.

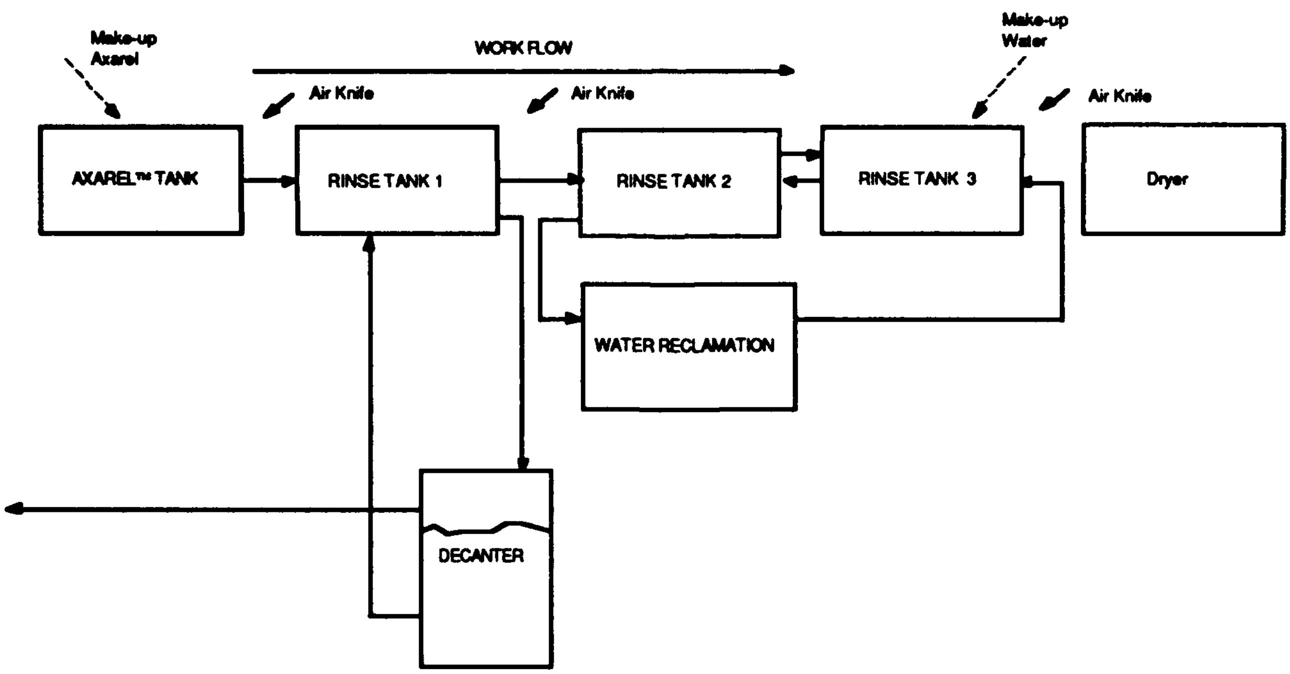

Figure 1. Advanced Semi-Aqueous Cleaning Machine

To minimize the amount of organic reaching a publicly owned treatment works facilities (POTW) facility, the lowest possible amount of organic material should be permitted to enter the rinse sections. In principal, the lower the emulsion concentration, the lower the amount of organic which is transferred into rinse sections two and three. The lowest practical emulsion concentration is the

minimum concentration that will separate in the decanter section of the cleaning machine. For example, the minimum emulsion concentration for Du Pont's Axarel® cleaning agents is about two percent.

By using an emulsion section in tandem with a decanter as the first rinse section in a semi-aqueous cleaning machine, it is possible to keep most of the semi-aqueous cleaning agent and the soils dissolved in the cleaning agent out of the rinse water.

THE SEMI-AQUEOUS CLEANING PROCESS: WATER RINSES

When parts exit the first rinse, they are coated with a thin layer of water/solvent emulsion. The average, measured dragout is about 10 grams per square foot of circuit board. The final rinse sections of the cleaning machine rinse this coating off. The equilibrium concentration of the semi-aqueous cleaning agent in the final rinse section can be estimated from the emulsion concentration, dragout, rinse water flow rate, operating time, and board throughput. Table 2 shows the calculated concentrations of organic material in rinse water effluent for several scenarios. For the actual case in the fourth column, the calculated concentration of semi-aqueous cleaning agent in the rinse tank was confirmed by measurement.

Table 2. Rinse Water Model

Variable	Case 1	Case 2	Case 3	Actual Case
Boards, sq. ft./yr.	500,000	500,000	500,000	100,000
Operation, hr./yr.	4,000	4,000	4,000	4,000
Rinse Water Flow, gpm	4	4	2	1.5
Emulsion Conc. , %	100	2	2	7
Dragout, g/sq. ft.	10	10	10	10
Conc. of Axarel™ 38, ppm	1,185	24	47	44
Measured Conc., ppm	-	-	-	40-50

The calculations and measurements show that the concentration of organics in the rinse water effluent will be low. The hydrocarbon-based cleaning agent, in the case of the Axarel™ cleaning agent product line, is non-toxic and non-inhibitory to bacteria. Most municipalities will allow low levels of organics to be discharged into a POTW[4]. Heavy metal concentrations in effluent from existing semi-aqueous machines have also been well below typical discharge limits. The adoption of any water treatment technology, regardless of its efficiency, will result in higher capital costs, increased operating costs, and added complexity. Users should carefully evaluate the effluent emission limits in their areas before making the decision to invest in closed-loop technology.

RECYCLING RINSE WATER

Despite the low level of organics in the rinse water, electronics manufacturers are looking for ways to better control or totally eliminate their waste streams. There are many reasons for this growing trend, including: increased corporate environmental awareness, limited water supplies, and existing or more restrictive government regulations.

Given the fact that users of semi-aqueous cleaning agents desire methods to recycle rinse water, Du Pont has investigated technologies for close-looping the rinse water.

An important consideration when choosing a rinse water recycling system for a semi-aqueous cleaning machine is how clean the rinse water must be to produce acceptably clean printed wiring assemblies. Many electronics manufacturers have established their own criteria for cleanliness. There are several measures of cleanliness, including: ionics, residual rosin, and surface insulation resistance. The Cleaning and Cleanliness Test Program sponsored by the EPA/DOD/IPC Ad Hoc Solvents working group has established a protocol for quantitatively comparing cleaning solvents.[5]

The effect of rinse water contamination on printed wiring board assemblies that were cleaned with Axarel™ 38 cleaning agent has been studied several times. The results of ionics and residual rosin studies were reported in earlier papers.[6,7] Both studies showed that printed wiring assemblies can be rinsed with water which is contaminated with at least 3,000 ppm (0.3 volume %) of Axarel® 38 and still meet the cleanliness requirements.

An expanded study was run to measure the effect of the concentration of Axarel® 38 in rinse water and the effect of flux residue in the Axarel® 38 cleaning agent. The effects were monitored by ionics, residual rosin, and SIR measurements. "D" boards were processed as defined in the EPA/DOD/IPC Ad Hoc Solvents test procedure. These boards have two surface mount components, which are vapor phase soldered, and plated through holes which are wave soldered with RA flux. After vapor phase reflow and again after wave soldering, the boards were cleaned in Axarel® 38 and then rinsed with rinse water that was contaminated with varying amounts of Axarel™ 38 and Alpha 1585 Mil RA flux residue. Table 3 contains a summary of the ionics and residual rosin test data. Printed wiring board assemblies cleaned in CFC-113/MeOH were used as controls for this experiment.

Table 3. Ionics and Residual Rosin Data

Solvent or Rinse	[Axarel® 38], Vol. % in rinse water	[Flux Residue], Wt. % in Axarel®	Ionics, µg/sq. in.	Residual Rosin, Abs.	Rinse Water Res., MegΩ
Used CFC-113/MeOH	-	-	6.9±0.6	0.84±0.14	
A	0.00	0	4.9±0.2	0.44±0.07	1.47
B	0.10	0	5.8±0.6	0.47±0.08	1.55
C	0.10	20	7.1±1.4	0.56±0.20	0.32
D	0.10	40	8.9±0.6	0.82±0.13	0.20
E	0.50	0	5.4±0.6	0.21±0.01	0.74
F	0.50	20	6.5±0.1	1.17±0.15	0.08
G	0.50	40	7.1±0.3	1.10±0.10	0.05
H	0.90	0	4.7±0.9	0.15±0.03	0.57
I	0.90	20	6.9±0.8	0.65±0.18	0.04
J	0.90	40	11.5±1.7	3.89±1.13	0.03
Fresh CFC-113/MeOH			7.4±1.7	0.45±0.11	

From these data, it is clear that circuit boards meet cleanliness standards even if the rinse water contains substantial amounts of this particular semi-aqueous cleaning agent and flux residue. Even a very conservative analysis shows that rinse water can be at least 0.1% by volume Axarel™, and that the flux residue concentration can be up to 20% of the total organic. Only boards rinsed in rinses D and J (both with 40% flux residue by weight) exceeded the ionics of the controls. One of the most striking conclusions is that the rinse water can have a fairly low resistivity. Based on ionic contamination data, rinse water with a resistivity of 0.04 megohms is adequate.

Surface insulation resistance (SIR) testing was conducted to simulate lifetime for circuit assemblies. In SIR testing, circuit assemblies are aged at 85% humidity and 85°C for over a week as prescribed in EPA/DOD/IPC Ad Hoc Solvents test procedure. The resistance between adjacent circuit features is measured over time. This test measures the resistances of 10 different electrical patterns on each B-36 test board over a 7 day test period. The test circuits are considered to have failed the test if the log of the resistance per square drops below 8.5[8]. According to the data, none of the rinse conditions caused the surface insulation resistance to decrease below the acceptance level, even after 168 hours in the environmental chamber. Results of the SIR testing for four of the ten test patterns, including the two most demanding test patterns, are summarized in Table 4.

Table 4. Surface Insulation Test Results

Solvent or Rinse	Log R/sq. for pattern 2 (168 Hours)	Log R/sq. for pattern 4 (168 Hours)	Log R/sq. for pattern 6 (168 Hours)	Log R/sq. for pattern 8 (168 Hours)
TMS	11.41	11.90	12.41	13.30
A	11.47	11.93	12.60	13.66
B	11.14	12.00	12.85	13.70
C	11.69	11.99	12.67	13.38
D	11.56	12.03	12.41	13.22
E	11.51	11.97	12.79	13.74
F	11.68	12.04	12.74	13.53
G	11.68	12.04	13.00	13.22
H	11.66	12.00	13.60	13.58
I	11.73	12.02	12.88	13.75
J	11.48	12.03	12.79	13.10

The rinse water model predicts that the concentration of semi-aqueous cleaning agent in the rinse water will never be very high. In fact, the maximum reasonable concentration of contaminants in rinse water is 400 ppm (0.04 weight percent) which is at least a factor of two below the most conservative conclusions from the rinse water contamination study and a factor of nearly 20 by a slightly more liberal interpretation .

MEMBRANE TECHNOLOGY FOR RECYCLING RINSE WATER

Several technologies have been examined in our laboratory for recycling rinse water from semi-aqueous cleaning machines. Both carbon adsorption/ion exchange and membrane technology were found to work. When rinse water recycling is required, membrane technology offers the best solution for high volume applications. The operating costs for carbon treatment in these applications are significant.[9]

In membrane technology, contaminated solutions are pumped under pressure through membranes that are designed to allow small water molecules to pass and to restrict the flow of ions and large molecules, such as those in the components of semi-aqueous cleaners. An important caveat is that not all membranes are created equal. One membrane may separate contaminants from water but may be ineffective or damaged when used to separate a seemingly similar contaminant from water. Figure 2 shows schematically how membrane systems work. Contaminants are concentrated in the reject stream and reduced in the permeate stream. While 100% separation is never achieved, well-chosen membranes can achieve better than 99% separation.

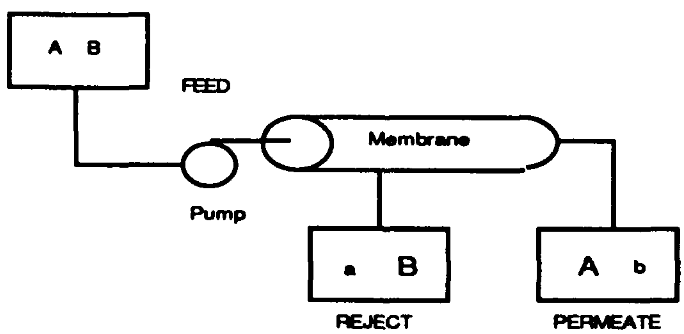

Figure 2. Membrane System.

The combination of semi-aqueous cleaning and membrane water purification technologies offers some unique benefits over other cleaning and water treatment systems.

Semi-aqueous cleaning agents phase separate from water at concentrations above 2%. Therefore, the emulsion/decanting sections of the cleaning machine provide a simple means of removing up to 98% of the organic contaminant from the board before it reaches the final rinse stages. In the decanter the residue-containing solvent phase separates from the water and is sent to a fuel burning program. The small amount of solvent which is carried into rinse stages two and three can be separated from rinse water by membrane filtration. The permeate is returned to the cleaning machine while the reject stream is sent back to the membrane feed tank. "Recycling" the reject this way results in a contaminant buildup in the membrane feed tank. When the concentration reaches approximately 2% organic, phase separation decanting can be used to remove the soil-containing solvent. With carbon absorption all of the organic material is absorbed into the carbon. Once saturated, the carbon is disposed of as a solid waste, or sent for costly regeneration.

Membrane systems are much better suited for use with semi-aqueous systems than they are with aqueous systems. In attempting to treat aqueous effluent with a membrane, there is no simple means of disposing of the reject. A membrane will reduce the overall volume of waste water, but will not reduce the total amount of solvent and soil to be disposed of. For example, membrane purification is viable for desalinating sea water because the reject, sea water with an increased salt content, is pumped back into the ocean. With semi-aqueous cleaning, the reject is decanted. No such convenient means of disposal exists for concentrated wastes which are soluble in water, like, detergents, saponifiers or alcohols.

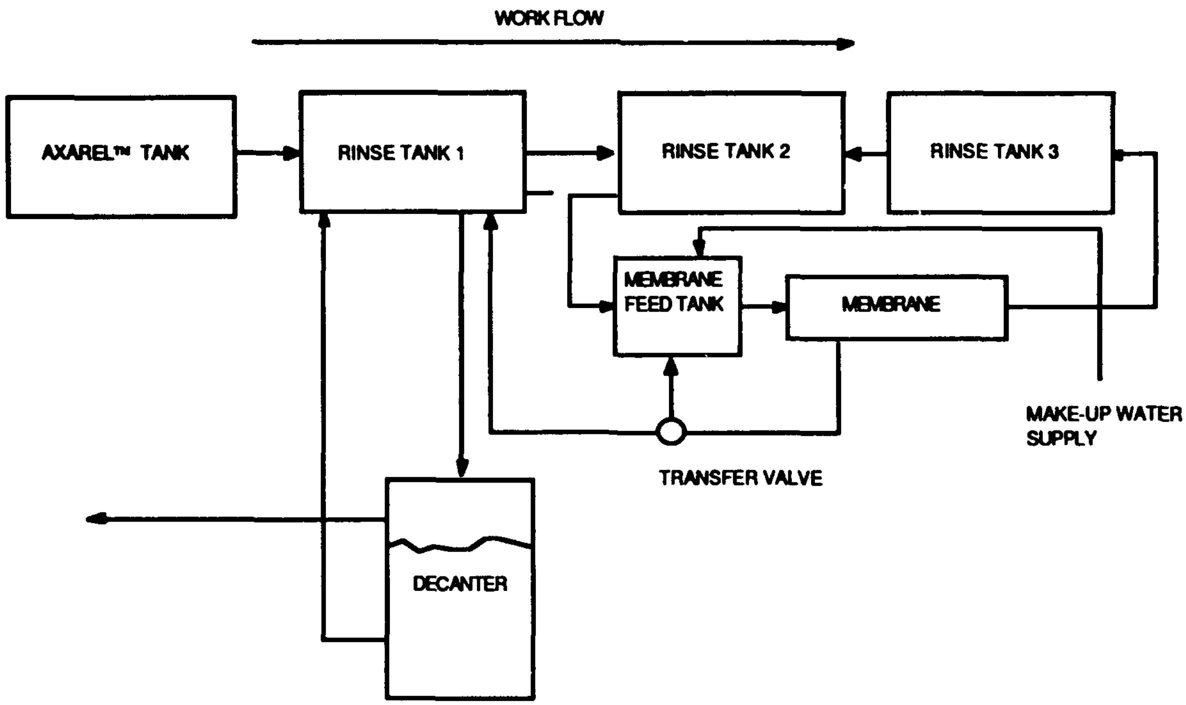

Figure 3. Semi-Aqueous Cleaning Machine Coupled to a Membrane System

A membrane system used in conjunction with semi-aqueous cleaning does not "consume" carbon, deionization resins, or any other water treatment media. Nor does it generate solid waste which must disposed of. All of the solvent, with dissolved soils, eventually leaves the system via the emulsion decanting system on the cleaning machine. The user only need replace the membrane filter periodically, at a relatively modest cost ($2000 to $5000 per year).

MEMBRANE SYSTEM/CLEANING MACHINE INTERFACE

The interconnection of a membrane system to a semi-aqueous cleaning machine consists of three pipes. (See figure 3) Rinse water flows out of rinse stage 2 into a lift station and is pumped into the membrane feed tank. From the feed tank, contaminated water is pumped to the membrane filter where it is split into two streams of equivalent volume. Permeate is the purified water which has an organic concentration of about 1% that of the feed tank. The Reject stream contains virtually all of the organic and is sent directly back to the feed tank.

This configuration will cause the concentration in the feed tank to continually increase. The third interconnection pipe allows for periodic transfer of this concentrated solution back to the emulsion/decanting system on the cleaning machine. The reject water is simply used to provide make-up for dragout and evaporative losses from the first rinse stage.

Rinse sections 2 & 3 will operate in an overflow configuration. Permeate flows into rinse stage 3, cascades into rinse stage 2, then overflows into the lift station and is sent back to the membrane system. Water make-up for the entire cleaning machine and membrane system is controlled by the feed tank on the membrane system.

PERFORMANCE RESULTS

A membrane system which is operating with a cleaning machine reaches a steady-state condition. A material balance around the entire emulsion, decanting, rinse and membrane systems, has only two inputs, solvent dragged into the first rinse stage, and make-up water. There are also only two outputs, solvent taken out of the decanter and evaporative loss. There are two key technical questions which must be answered. First, what will the organic concentrations in the various rinse stages be, once a steady-state condition is achieved? As stated above, the quality of the permeate is inversely proportional to the quality of the feed. Even though the membrane removes approximately 99% of the organic and ionic contamination from the rinse water, concentrations in the final rinse stage could be in the 100 to 200 ppm range. The second, and more critical question is, once we establish a steady-state condition, can we get good cleaning? Our rinse water contamination studies[10] show that we can expect good cleaning, but it must be verified in an actual system.

Table 5. Cleaning Machine/Membrane Operating Conditions

SA-20 Conveyor Speed (During IPC-B-36 Cleaning)	2 fpm
SA-20 Conveyor Speed (All Other Times)	6 fpm
Board Throughput (Topside Area)	30 ft^2 per hour
Solvent Temperature	160°F
Rinse Temperatures	140 - 150°F
Permeate Flow Rate	1.5 gpm

A commercial scale membrane system was set up in our laboratory and connected to a Detrex SA-20 in-line Semi-Aqueous cleaning machine. A two-week test was conducted to establish a steady-state operating condition and measure cleaning performance under these conditions. During the evaluation, the machines were run for eight hours per day. Table 5 shows the operating conditions of the machines during the test.

The Detrex SA-20 has a continuous belt, so a high belt speed, along with the board loading provided dragout of solvent from the wash module into the rinse stages. During the cleaning cycles for the B-36 test boards, the conveyor speed was reduced to 2 fpm, which is the standard speed adopted for work in our laboratory. Permeate was delivered from the membrane system to the cleaning machine at a rate of 1.5 gallons per minute throughout the test. Organic concentration and the conductivity of various rinse stages were used to determine when a steady-state condition was reached. Table 6 shows the concentration and conductivity levels in all rinse stages for the duration of the test.

Table 6. Rinse Water Quality

Day	1ST Rinse (Emulsion)		2ND Rinse		3RD Rinse	
	Total Organic Concentration (ppm)	Conductivity (micromhos)	Total Organic Concentration (ppm)	Conductivity (micromhos)	Total Organic Concentration (ppm)	Conductivity (micromhos)
1	14,600	180	210	13	45	5.7
2	27,100	190	1,300	24	85	11
3	24,000	200	630	24	125	13
4		210		49		32
5	16,700	200	300	20	105	17
6		240		38		14
7	27,100	250	315	28	105	18
8	25,000	250	210	21	85	15

The data above shows that we have established an equilibrium in the ranges that we would have predicted. Organic concentration levels will tend to fluctuate during the test due to changes in board throughput. The conductivity readings are somewhat high, but still within the ranges that previous studies, outlined earlier in this paper, have predicted should yield good cleanliness results.

During the test, IPC-B-36 benchmark boards were soldered, and cleaned in the SA-20. Ionic cleanliness, residual rosin and surface insulation resistance (SIR) were measured. Boards cleaned in a two-sump vapor degreaser with a CFC-113/Methanol azeotrope were used as controls. Table 7 and 8 summarize the ionics, residual rosin, and surface insulation resistance results for both Axarel™ 32 cleaning agent and 113/MeOH.

Table 7. Ionics and Residual Rosin Data

	Ionics (µg NaCl eq/in^2)		Residual Rosin (µg/board)	
Day	Axarel™ 32	113/MeOH	Axarel™ 32	113/MeOH
1	7.6	7.2	306.8	1112.6
2				
3	6.6	7.8	174.9	1252.0
4				
5	7.2	7.4	166.3	1175.3
6				
7	6.9	8.0	291.7	1492.5

Table 8. Surface Insulation Test Results

		Log R/sq. Pattern 2 (168 Hours)	Log R/sq Pattern 4 (168 Hours)	Log R/sq Pattern 6 (168 Hours)	Log R/sq Pattern 8 (168 Hours)
Day 1	Ax 32	11.79	11.59	12.62	13.81
	TMS	11.51	11.67	11.44	13.92
Day 3	Ax 32	11.00	11.46	12.32	13.57
	TMS	11.07	11.79	12.27	13.80
Day 5	Ax 32	10.93	11.23	12.57	13.76
	TMS	11.10	11.53	12.47	13.30
Day 7*	Ax 32	7.10	11.91	11.82	13.50
	TMS	7.87	12.16	12.05	13.59

* These data were affected by SIR equipment shutdown and the dehydration and rehydration that resulted.

Following the establishment of a steady state condition, the Axarel™ ionics results were very good when compared to CFC-113/MeOH. Residual rosin levels were well below the control samples and there was essentially no difference between the two solvents in SIR results. These two groups of data demonstrate that in this test, excellent cleaning was achieved while using a membrane filtration system to recycle the effluent from the final rinse stages.

A second control experiment was conducted by returning the Detrex cleaning machine to DI water operation. During this experiment, deionized water was continuously fed at the rate of 0.5 gallons per minute. Temperature profiles throughout the wash and rinse stages were the same as in the earlier test. An effort was made to maintain the organic concentrations at the lowest possible level in all rinse stages, so no extra boards were run through the machine to increase dragout. Table 9 compares the results of this DI water control test with day 7 of the membrane water test described above.The organic concentrations in the final rinse stages during the control experiment were significantly lower than during the membrane experiment, as were the rinse water conductivities. In spite of this the ionic and residual rosin cleanliness results for the two tests were similar. This is further evidence that a membrane water purification unit can be used to efficiently remove contamination from rinse water while maintaining the high degree of cleanliness typical of semi-aqueous cleaning.

Table 9. Comparison of Membrane-Treated Rinse Water and Deionized Water

		Membrane Experiment Day 7	DI Control
Rinse Stage 1	Organic Concentration (ppm)	27,100	3,100
	Conductivity (micromhos)	250	300
Rinse Stage 2	Organic Concentration	315	100
	Conductivity	28	8
Rinse Stage 3	Organic Concentration	105	0
	Conductivity	18	2
Ionics (μg eq. NaCl/in^2)		6.9	7.9
Residual Rosin (μg/board)		292	404

SUMMARY AND CONCLUSIONS

In semi-aqueous cleaning equipment, organic material is transported from the solvent chamber on printed wiring assemblies to the rinse sections of the cleaning machine. The most efficient way to remove the cleaning agent from the printed wiring assemblies while protecting the environment is a two-stage process.

Most of the organic material is removed in the emulsion section of the cleaning machine. The emulsion is discharged to a decanting system where the bulk of the organic material is separated from the water. The water is returned to the emulsion tank and reused resulting in no water effluent from the emulsion/decanting system.

The small amount of solvent and soil remaining in the rinse water can be efficiently and economically removed using membrane filtration techniques. The connection of a membrane system to a semi-aqueous cleaning machine will yield a steady-state operation which gives very good cleaning. Ionic and residual rosin contamination levels are below results obtained using a CFC-113/MeOH azeotrope, and comparable to results achieved when using a semi-aqueous cleaning process with continuous DI water feed.

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MR. CHIP AND THE ESD WORK STATION

by

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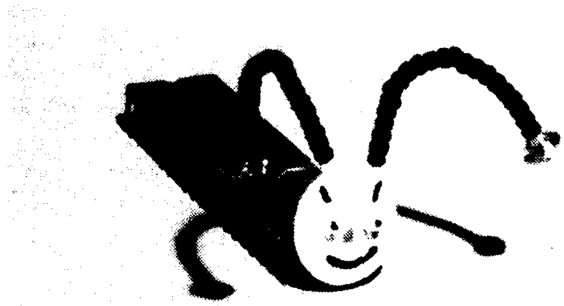
ABSTRACT

This paper describes and discusses the basic ways we need to protect Mr. Chip around the ESD work station. Items such as proper grounding, work surface material, work surface cleaning, wrist strap, flooring, equipment and chairs will be evaluated.

INTRODUCTION

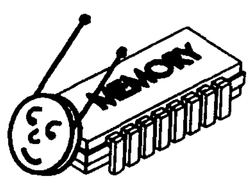
MEET MR. CHIP

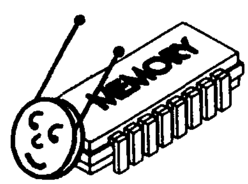


HE'S LARGE, HE'S SMALL, HE'S DELICATE, HE WORKS WONDERS AND HE CONTROLS A LOT OF OUR LIVES

HIS PRESENCE IS EVERYWHERE. He is in our hearing aid, in our heart pace units, he helps the blind see, he controls our bank account, our car, our computer, our TV, our telephone, the airplane we fly in, the check out station at the grocery store, even our sports are controlled by Mr. Chip. We don't see him but he is always there.

Mr. Chip and all his buddies are very sensitive to Electro Static Discharge (ESD). ESD can cause havoc with Mr. Chip and we the people generate a lot of static electricity. We keep hearing that they are going to harden these chips so static charges will not affect them. This process is having a difficult time keeping up with the design.





SET UP OF ESD WORK STATION

First, we have to determine what we need at an ESD work station (Figure 1). Proper Grounding around the work station is essential. Do we need a grounded work surface? Yes, we do. Do we need to ground the cabinets and drawers if they are part of the bench? Yes, they need to be grounded if they are utilized to store sensitive ESD items. If there is a workshelf on the bench, it should be a groundable surface.

Most bench top work surfaces are hard laminates. This hard laminate should be the ESD type known as static dissipative material which has a built in resistance. This built in resistance will bleed the charge slowly through the ground wire to the proper ESD ground. There are two other types. One is antistatic and the other is conductive. Antistatic will prevent a static charge from being generated. The disadvantages of this material are a limited shelf life, hard to test, usually a soft material and does not stand up under hard use.

Highly conductive material, such as a metal work bench top, can be very dangerous to the worker if a live wire falls on it. Also a rapid discharge current can occur if a charged sensitive Printed Circuit card is placed on it.

Grounding of ESD work stations established in buildings in the United States will use the common green wire equipment ground for grounding purposes. The green wire is recognized by the National Electric Code as the proper ground. The green wire will be connected to each outlet box on the work station following the National Electric Code. Grounding of the work surface must follow local regulations which vary from country to country. Any power equipment utilized on the bench should have a green wire ground. This green wire will tie into the white wire back at the main circuit breaker box in accordance with the National Electric Code. I have visited a couple of companies and depots where they have actually drilled a hole through the concrete floor and driven a ground rod down through the hole into the soil. This is not a proper ground and can cause some very interesting problems.

A grounding standard has been written by the EOS (Electrical Over-Stress) /ESD Association and is recognized by ANSI. This standard covers the proper ground procedure to ground an ESD work station to the green wire ground. It also gives test procedures for testing. At this time DOD is evaluating this standard for use in military application.

Going back to the top of the bench, most surfaces are very hard ESD laminant material which is difficult to work on. The Printed Circuit Board has a tendency to slide around on the hard laminant. Also it can damage delicate connectors and components on the board.

So can we put a softer pad on it? Yes, but you should evaluate the different types of ESD pad material and find one that works the best for you. The two basic types are homogeneous volume resistance and a type with a buried conductive schrim layer. The homogeneous material does not need a separate wire to ground. The ESD charge will pass through the material to the hard ESD laminant. Be careful about workers who like to store their papers under this type of pad. The second type contains a buried conductive schrim layer which has to have a groundable point and a wire going to the proper ground even though the ESD hard laminant is grounded. Also, only one side of this type of material can be used because it usually has some type of insulated material on the bottom of the pad.

To measure these work surfaces accurately a megohmmeter should be used with two five pound electrodes described in NFPA 99. The megohmmeter should have a range between 1×10^5 and 1×10^{10} in resistance and a test voltage between 10 volts and 200 volts DC.

There are some simple test methods and equipment that can help you check for ground, but they do not give accurate readings only Go/No-Go which is alright for a quick check for proper ground.

For proper measurements of the work surface resistance reference EOS/ESD Association Standard S 4.1, Work Surfaces-Resistive Characterization.

BENCH TOP LAMINANT

Let's take a look at the hard ESD laminant and the ground bolts that ground the ESD laminant to ground (Figure 2). Most of the older hard laminants have a buried black carbon Schrim layer which is highly conductive under the hard top surface. This makes it easy to see when you counter sink the hole. Some of the new laminants have a white type of conductive material making it harder to identify the buried conductive layer.

We should be careful if we wear the top surface off. You will end up with a very conductive bench top. This can be a good reason to use an ESD pad on top of the hard ESD dissipative laminant.

To properly install the ground bolt or bolts into the laminant, a hole is drilled through the hard ESD laminant all the way through the bench top (Figure 2). The top part of the hole is then counter sunk. This allows the flat head bolt to make contact with the conductive layer.

There are other type bolts that will work. Be careful if a carriage bolt is used. I have run into many instances where carriage bolts have been reversed in the hole and a flat washer and wing nut put on the top side. The flat washer will not bite though the top laminant to make contact with the conductive layer. Only the shoulders of the carriage bolt will dig into the hard laminant.

To make it easier to test the ground bolt contact with the carbon layer, some bench manufacturers are installing two ground bolts. The bolts should be at least 12" apart, preferably one at each side of the bench (Figure 1).

A resistance reading with an Ohm meter from bolt to bolt will indicate that they are making contact with the carbon layer. If only one bolt is supplied by the manufacturer, then you have to locate some part of the bench top where the conductive layer is exposed for the second contact point.

CLEANING THE WORK SURFACE

A mild soap and water can be used to clean the ESD work surface. When you clean the hard laminant, be careful about getting the cleaning liquid in and around the grounding bolts. Corrosion can cause loss of a good ground.

WRIST STRAP

The most important item at the ESD work station is the properly grounded wrist strap. The wrist strap and cord have a series one megohm resistor, known as a current limiting resistor. Ground for the wrist strap should be direct to green wire ground not to the bench ground.

If the bench ground required a one megohm resistor in the ground circuit, this could cause a higher resistance than required from wrist strap to ground. The wrist strap should be constantly monitored or checked at least twice a day. A loose wrist strap or dry skin can cause problems with proper skin contact. There are ESD hand lotions which will help dry skin.

There are many types of wrist straps out there. Most all of them do a good job. But durability and the life expectancy should be evaluated when purchasing wrist straps. At the Sacramento Army Depot I have found that the velcro and cloth type get dirty faster and lose their ability to make good contact with the skin. Also they have a short life expectancy compared to the metal flexible watch band type.

Some employers believe that the metal watch band type is dangerous because it is all metal and a person could receive a shock. If you are working around high voltages you should not be wearing a wrist strap.

The wrist strap connecting cord should be plugged in somewhere near the front edge of the bench. If it is plugged in at the back of the bench, the wire could catch on the items that are being worked on or other equipment on the bench.

FLOORING

Heading down to the floor of the ESD work station we need to know what type of floor material is present and what is required. A cement floor makes a very good ESD floor. The consistency of the cement and the rebar do a very good job of keeping down static generation. But people don't like to work on cement floors. Also it always looks dirty and cannot be used for clean rooms.

When a cover such as tile, epoxy or carpet is placed on a cement floor to make it look nice, we need to check to see what static charge can be generated (Tribo Charging). Good ESD floors such as tile, epoxy and carpet are very expensive but they do work when a person wears proper ESD footwear. Most ESD floor advertisements mention very little about proper footwear.

Whether you decide to put down tile, epoxy or carpet these ESD materials need to be grounded.

Be careful if you use an ESD floor pad. Some of them are very conductive. If someone came to work with wet shoes and started working with high voltage, a severe shock could be received.

If you have a regular tile or epoxy floor all is not lost. There are some good ESD floor finishes (wax) out there. They are not cheap and a good maintenance and janitorial service is required. I have found at the Sacramento Army Depot that if the janitor does a good maintenance job on the floor there is very little charge generation. In a couple of areas at the Sacramento Army Depot, I have managed to leave out the ESD shoe or heel strap requirement. When it comes to buffing the floor finish, be very careful about high speed buffing. It can ruin a good ESD floor finish (wax).

The EOS/ESD Association is completing a standard and test procedures for ESD floor material. EOS/ESD-DS7-1 1992 Floor Materials Resistive-Characterization of Materials is in draft form now and out for evaluation. When completed it will be ANSI approved.

A few recommendations I have on purchasing an ESD floor. Do a lot of evaluations on types of material. Figure out what voltage you can work to and how sensitive your chips and boards are. Look for a contractor who has experience installing ESD flooring.

One of the important things is running acceptance tests on the floor. Who will do the testing? You can have a private test firm do it, do it yourself or have the contractor who put the floor down run the test.

Be sure whoever does the testing knows what type of testing is required. I know of one case where the manufacturer of the floor material called out MIL-B-81705B test in his advertisement literature. This test calls for the item to be charged to 5000V and then discharged to less than 50V in two seconds or less. When it came time for the contractor, who had put the floor down, to test to this standard he said he could not run the test. He stated that MIL-B-81705B is only a test for ESD bag material.

You may want to write some of your own test requirements. How the floor is grounded is very important. I rejected one of my ESD epoxy floors for not meeting our requirements and the contractor had to come back and put another one down. Neither one of us was happy about this. It cost the contractor and it cost the Sacramento Army Depot production time.

EQUIPMENT

Going back to the top of the work bench, small bench ionizers if required, should be checked at least once a month. Do not let other equipment block the air coming from the ionizer. Soldering irons or stations with large plastic cases that house the power supply for the iron should be static dissipative material or coated with a good static dissipative paint. There are some good coatings out there also.

Small hand tools with plastic handles such as pliers and screw drivers are not a large problem. The person who uses this type of tool should be wearing a wrist strap. If any tools have a static charge on them, it will be bleed off by either the person's wrist strap or as they are placed on the ESD work bench. One other item that needs to be mentioned is a brush to remove dust and dirt from the printed circuit board. Any dry brush that is used to clean the printed circuit will generate a charge. The only thing that will help this situation is a damp brush or a brush dampened with alcohol or a recommended cleaning solution.

CHAIR

One item that has not been mentioned yet is the ESD chair. There are companies that sell quality ESD chairs. The only problem with the ESD chair is that a static dissipative floor is needed to remove the charge from the chair.

A non-ESD or synthetic chair material can generate charges as you move around on the chair. One way to eliminate this problem is by spraying it with an antistatic solution; but how often can it be sprayed before it becomes sticky? Remember an ESD chair has to have some type of ground. Most of the time the chair has a drag chain or conductive caster to ground it to the ESD floor.

If you don't have an ESD floor or pad you have a problem. About the only solution is to ground the ESD chair to the work bench with a wire. This is not a very good practice. We now have a safety problem which is a wire to trip over. A good ESD floor finish will help cut down static generation as the chair moves around. The wrist strap will help a lot if it is placed on the wrist before a person sits down in the chair.

CONCLUSIONS

Top engineers around the world are still scratching their heads on how to eliminate the static problem. I doubt that we will ever solve it completely but there are many ways to reduce static problems such as raising the humidity, retaining the old cement floors, using proper ESD equipment and wearing cotton clothing as well as old leather shoes with holes in the bottom or better yet removing all clothing or running around in one's bare feet. This could create a safety problem for the safety personnel.

One thing I would like to emphasize is Buyers Beware. Obtain detailed information on ESD items before you purchase them and be sure they will do the job for you. Don't forget about the guarantee and maintenance of the equipment.

The Sacramento Army Depot purchased an Ion System a couple of years ago and the manual that came with it stated it was maintenance free. Don't believe it. The maintenance cost so much we shut it down. Spending a couple of thousand dollars on an ESD work station can help protect many items worth tens of thousands of dollars.

In conclusion don't forget you and I fly in airplanes and drive cars that are controlled by Mr. Chip. We don't want him to kick the bucket at the wrong time. It is very hard to prove that Mr. Chip could be guilty of causing the accident.

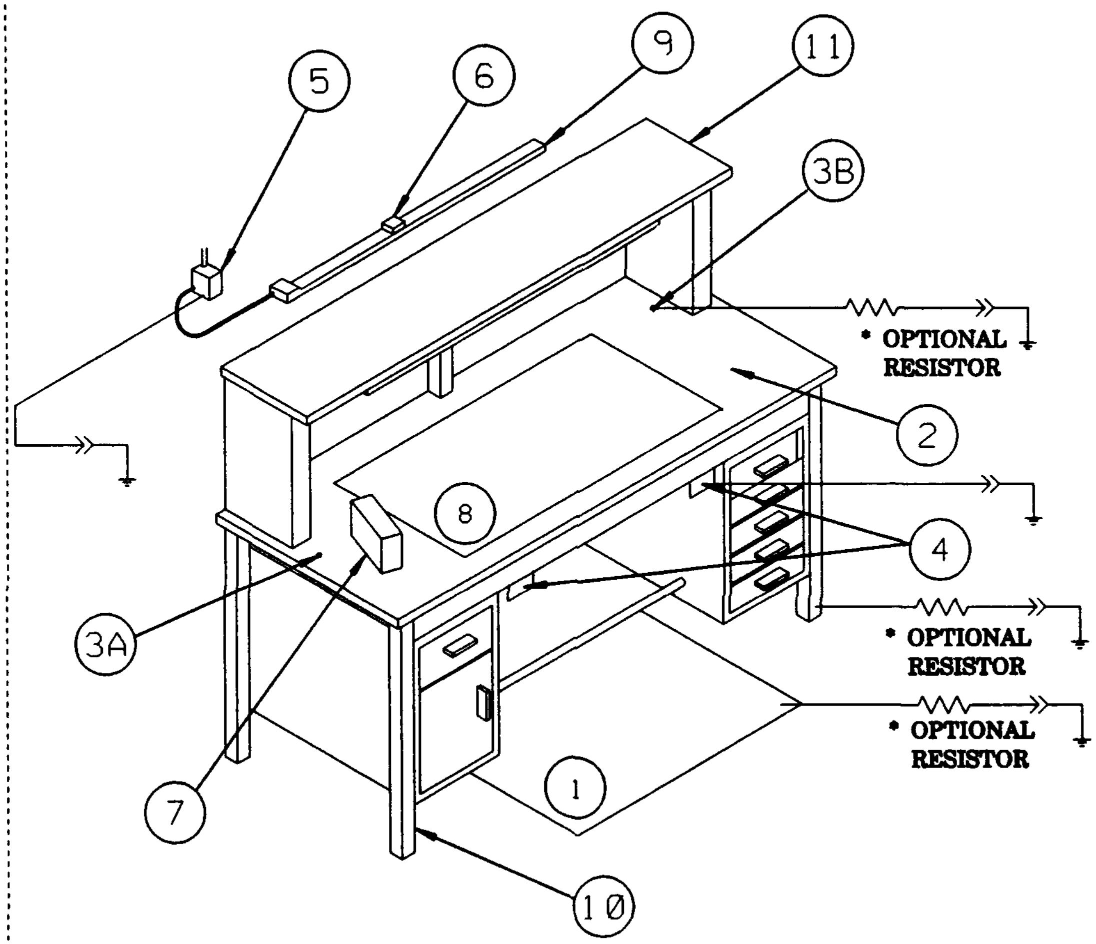


FIGURE 1. E.S.D. Work Station

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Reference for FIGURE 1
E.S.D. WORK STATION

1. Static Dissipative Floor Mat
   If required, connect to green wire ground.,
   One Megohm resistor optional
   Floor mat does very little good if the
   heel straps or conductive shoes are not worn.
2. Static Dissipative Work Surface Laminate
   Connect to green wire ground.,
   One Megohm resistor optional.

3A. & 3B. Contact Points
   Groundable points to inner layer work bench surface.
   also used as test points.
   Test point locations are optional.

4. Wrist Strap Plug-In
   2 per bench
   Connect directly to green wire ground.
5. Power Junction Box
   If Bench rquires power.
   110 AC ground fault circuit interrupters (GFCI's)
   may be required.
6. Wrist Strap Tester or Monitor - (REQUIRED)
7. Ionizer/Monitor - if required
8. Static Dissipative Pad - if required
9. 110 Volt Power Strip - Gounded
   avoid grounding to ESD work surface.
10. Bench Base & Drawers. (Metal)
    If used to store ESD sensitive items, need to
    be grounded.
    One megohm resistor optional.
11. Instrument shelf - if required.
    Should be static dissipative, also should be grounded.

NOTE: Electro-Static Discharge ESD equipment
can be tied to one common ground point
on the bench, excluding the wrist
strap plug-ins.

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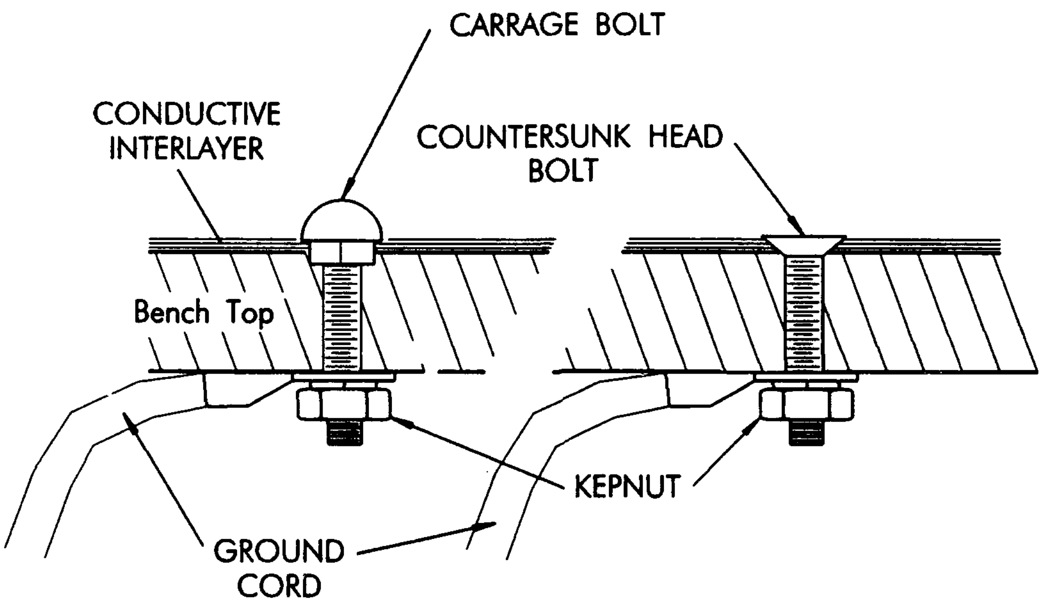

FIGURE 2. Bench Top with Ground Bolts

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Charles holds an AA degree in Electronics from Sacramento City College. He is a member of the EOS/ESD Association and is active in the Association's committees for grounding, flooring, equipment, and military liaison.

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PICOLITER FLUX DISPENSING FOR PRINTED WIRING BOARD ASSEMBLY

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ABSTRACT

A novel approach for precise and accurate solder flux dispensing is presented. This technique called picoliter flux dispensing, utilizes demand mode "ink jet" printing technology to deliver a controlled volume of flux to a designated target. The applicability of this technique for two different flux soldering processes, "no clean" hot bar soldering and mass reflow soldering with tacky flux, is investigated. Both processes require accurate, low volume flux deposition. Results of these studies, conducted with a laboratory system, are contained herein. Experiments with several isopropyl alcohol based, "no clean" fluxes demonstrate that 65 picoliter volume resolution and 0.33 microliter/second flow rates are attainable. Pull test results of hot bar soldered joints are given for various flux activator quantities. Results from tacky flux dispensing studies determined the flux and thinner amounts required for jetting at temperatures near 100 degrees C. The results of jetting, dot dispensing and tack tests are also presented.

INTRODUCTION

For the electonics board assembly arena three future trends are directly affecting the need for new dispensing technologies. These are the further minaturization of circuit assemblies, CAD driven assembly, and the no clean flux soldering processes. The new manufacturing processes developed in light of these trends will require greater precision for dispensing fluids. Such dispensing will be in a computer data driven printing mode as opposed to a hard tooling mode with stencils and masks. This precision printing may be for conventional fluids such as adhesives, solder pastes, and fluxes; or may be for some new type of fluid.

Picoliter fluid dispensing, a utilization of demand mode "ink jet" printing technology, promises to offer solutions to some of these dispensing requirements. Figure 1 dramatically illustrates the ability of such a system to dispense uniform droplets in tens of picoliter volume resolutions. Here, two 50 micron diameter droplet streams generated at over 4000 droplets per second converge into a single stream. This photograph was taken with a one second exposure while the droplets were stroboscopically illuminated, representing a sum of several thousand droplet stream occurances. By noting the spatial and dimensional uniformity of the droplet stream, even to the sharply focused, nonspherical deformation characteristics of the combined stream, the orders of magnitude differences with the conventional electronic manufacturing dispensing technologies can be appreciated.

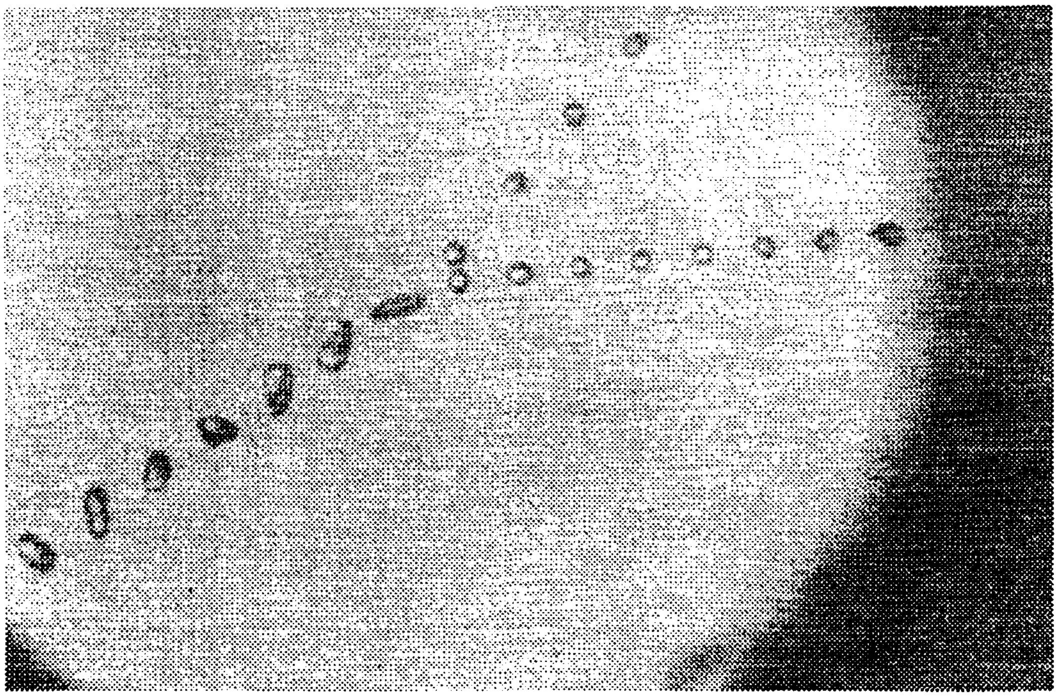

FIGURE 1. Dispensing of Droplets.

The utilization of picoliter fluid dispensing has recently been investigated for a variety of fluid dispensing problems, and is presented in Reference 1 thru Reference 5. This paper investigates picoliter flux dispensing for precision printing of flux. Applicability to two very different soldering processes, "no clean" hot bar soldering, and mass reflow soldering with tacky flux is investigated. The test results presented demonstrates the feasibility for these two different soldering processes using picoliter flux dispensing.

DISCUSSION

Demand Mode "Ink Jet" Dispensing Module

The first record of uniform droplet generation was made by Savart in 1831 (Reference 6). From the 1870s thru 1890s Lord Rayleigh performed comprehensive mathematical analysis of this phenomena (Reference 7 thru Reference 8.) In 1931 Weber's (Reference 9) work simplified the droplet formation model and made it more useful. In these systems fluid was jetted out of an orifice under pressure. If left undisturbed the fluid exited the orifice as a cylindrical column of fluid, but with certain periodic perturbation at a point on the diameter, the perturbation traveled axially, growing in diameter until the pertubation diameter equaled the diameter of the undisturbed fluid column and a droplet of fluid was formed. This phenomena is known as continuous mode jetting. For the printing industry one of the most common schemes for applying this is to charge and deflect jetted ink droplets onto the desired paper location. In the non-printing state the droplets are deflected into a catcher. Some of the work done in these systems is given in Reference 10 and Reference 11.

For electronic manufacturing the disadvantages of these continuous mode systems include the need for a catcher/fluid handling system, and potential charge accumulation effects onto circuit substrates. Demand mode jetting is an alternative class of jetting used in impulse, and thermal (bubble) jet technologies. In these types of systems a single droplet can be dispensed on demand, thus eliminating the need for a catcher and droplet deflection system. One of the first demand mode systems designed in the 1950's is an impulse jet driven by a piezoelectric transducer (PZT). The theoretical and experimental work on this design is presented in Reference 12 thru Reference 15.

The picoliter flux dispensing work described in this paper was done with an impulse jet. It consists of a glass tube that is drawn into an orifice on one end, connected to a fluid source on the other, and bonded to an annular piezoelectric crystal in the middle (Figure 2). Nickel electrodes are plated on the inner and outer cylindrical surfaces of the piezoelectric tube. The glass tube and piezoelectric crystal are assembled into a housing with a fluidics connection (Figure 3). Because of the straight through flow characteristics of this device, it is relatively easy to load without trapping air bubbles, which would prevent operation, and it is also relatively easy to clean.

The piezoelectric tube changes in diameter when a 30 microsecond voltage pulse is applied to the electrodes. The volume inside the glass tube also changes, since the glass is bonded to the piezoelectric crystal. The sudden volumetric change that

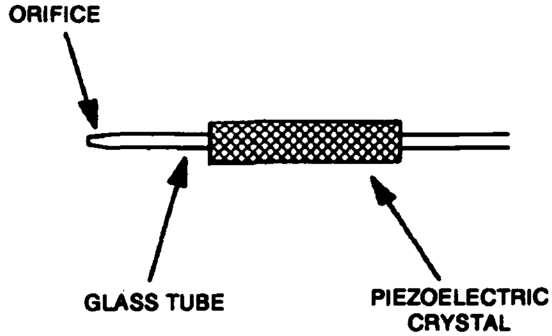

FIGURE 2. Impulse Jet Device

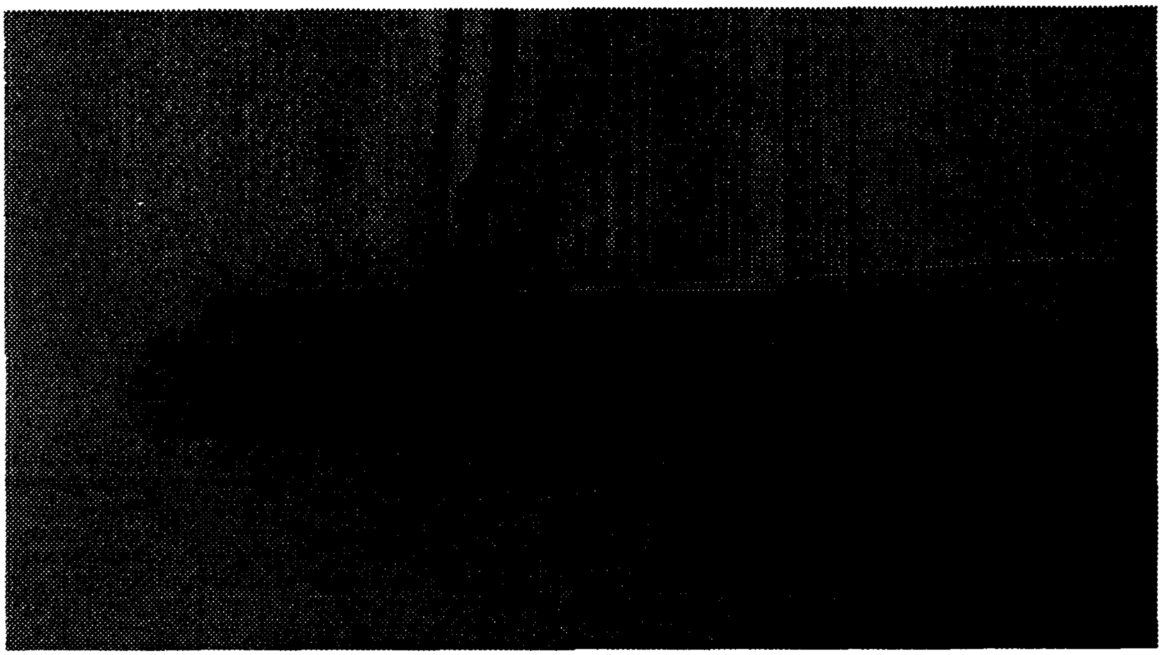

FIGURE 3. Impulse Jet Device.

accompanies the voltage pulse causes pressure and velocity transients to occur in the fluid. Finally, these transients are directed to produce a droplet that issues from the orifice. Normally, the droplet diameter would be close to the size of the orifice. Since a voltage pulse is applied only when a droplet is desired, these types of systems are referred to as drop-on-demand or demand mode systems. The velocity and size of the droplet are functions of the magnitude of applied voltage pulse. Larger voltage produces faster and larger drops. If the voltage is too low, no droplets will be formed. Voltages that are too high can damage the device. Maximum operating voltages at room temperature for a typical device is 80 volts.

The fluid jetting behavior of the device is characterized both quantitatively and qualitatively. Spatial positioning accuracy is determined by the variation of droplet velocity with the frequency of droplet creation. Spatial uniformity of fluid deposition is determined by the variation of droplet volume, or mass, with the frequency of droplet generation. These quantitative measurements must also be accompanied by a droplet formation assessment and an evaluation of reliability related to non-ideal fluid effects such as drying, and solids build up.

In order to characterize a fluid and device the jetting fluid's droplet velocity and mass is measured as a function of frequency over a range of 2 to 5 KHz. Droplet velocity is measured by the wavelength or distance between drops that have been "frozen" in space by a strobe (Figure 4). The velocity of the droplets is given by

$$v=\lambda f \tag{1}$$

where λ is the distance between droplets and f is the pulsing frequency. The average droplet weight, w_d, is given by

$$w_d = \frac{w_s}{ft} \tag{2}$$

where w_s is the weight of the sample, f is the pulsing frequency, and t is the time interval. The density of the flux was determined by weighing a known volume of flux. The droplet weight was determined by dividing the droplet weight by the flux density. As a standard set-up condition the voltage to the device was determined by jetting droplets at 3 m/sec and 2 KHz. A Picoliter fluid dispensing module generates and delivers small fluid droplets individually or in rapid succession. When implemented with a 50 micron diameter orifice, 50 micron diameter fluid droplets 65 picoliters in volume can be dispensed at flow volumes up to .33 microliters/second.

"No Clean" Hot Bar Soldering

Current methods of flux dispensing used in conjunction with hot bar soldering technology do not provide printing control sufficient to prevent flux from being needlessly deposited outside of the target pad pattern. This flux may not be sufficiently heated by the hot bar thermodes in order to first activate than deactivate the flux. Typically, hot bar soldering of fine pitch components is the last step in the PWB assembly process and so the assembled board will not go through a mass reflow oven to deactivate any residual activators after hot bar soldering. Consequently,

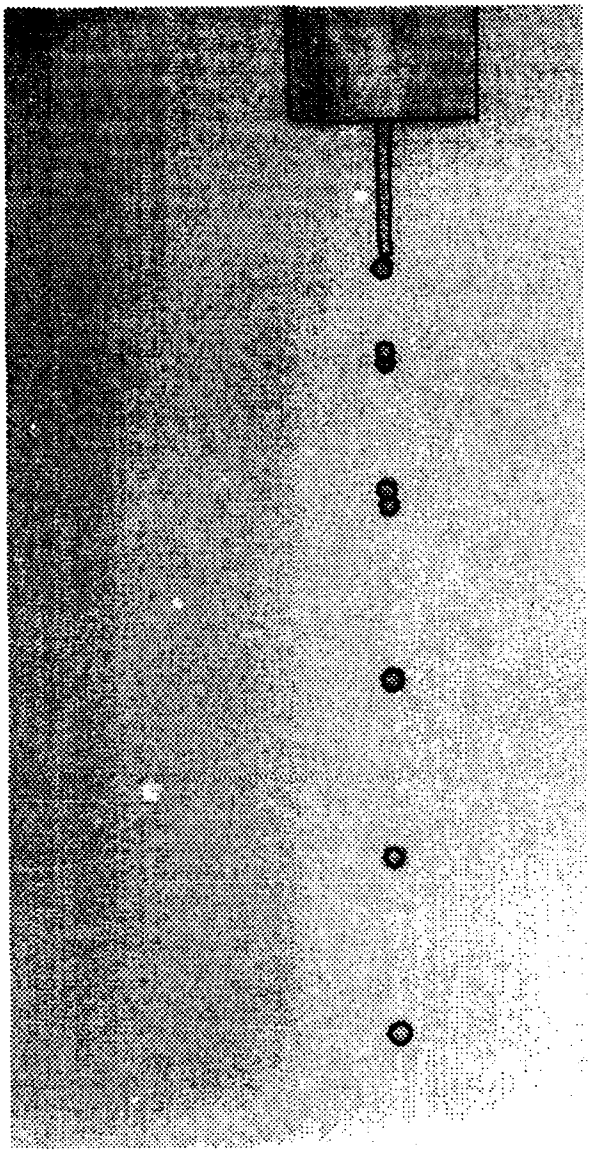

FIGURE 4. Droplet Generation from the Orifice.

concern exists that for certain types of "no clean" flux this activator residual constitutes a potential contamination problem for "no clean" board assembly processes.

With picoliter flux dispensing ultra precise printing control could eliminate any possible PWB contamination. Two distinct dispensing patterns were attempted. These are the fine line printing (Figure 5) of only the pads, and wide line printing of the pad pattern (Figure 6). In both cases flux should extend minimally beyond the pad length dimension boundaries.

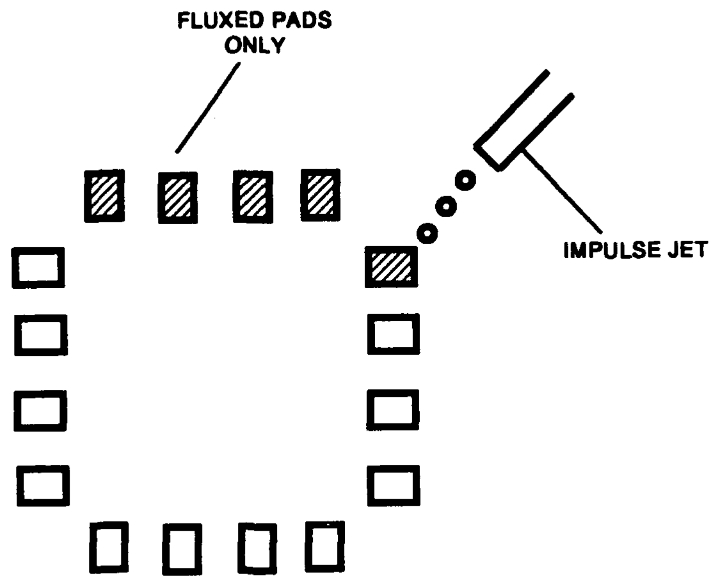

FIGURE 5. Fine Line Pattern

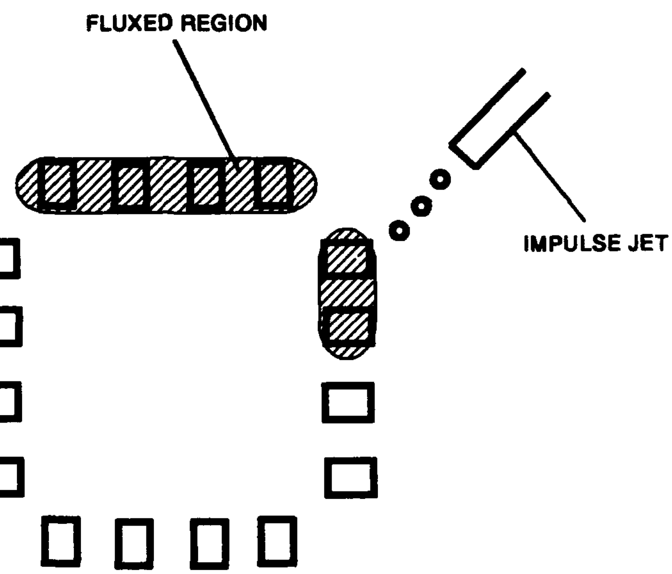

FIGURE 6. Wide Line Pattern

In order to determine the feasibility of achieving a "no clean", fine pitch hot bar soldering process, three tests were performed. The first was to characterize the fundamental fluid and jetting properties of selected alcohol based low solids content "no clean" fluxes. The second was to print fine line, and wide line patterns onto a 15mil pitch, 8 mil wide, pad pattern for a 188 pin TAB package. The third test was to determine solder joint quality having the pads picoliter dispensed with flux, and hot bar bonding 15 mil pitch TAB parts. Procedurally, flux is deposited, components placed, and hot bar reflow performed. Selected joints are then tested (pull test and cross section inspection). This procedure is repeated for various volumes of deposited flux. The pull test criteria and joint cross sectioning will demonstrate the amount of flux necessary to produce acceptable solder joints.

Mass Reflow With Tacky Flux

Mass reflow soldering with tacky flux is a surface mount process which does not use conventional solder paste. The PWB initially has the solder clad to the pads. Dots of tacky flux are dispensed onto the PWB's pad sites which are next populated with components. The boards lastly go through a mass reflow oven for soldering. The flux acts to tack down the component onto the PWB as well as to deoxidize the pad sites during the soldering cycle.

With this process the increasing minaturization of components requires smaller volumes of flux dots to be placed onto the pad sites. The conventional syringe dispensing systems cannot print such small flux dots. Therefore picoliter flux dispensing technology is being investigated as a method for printing the smaller quantities of tacky flux. The investigation will deal with the currently used tacky flux, and also its thinner and less viscous versions. The flux has a room temperature viscosity in the range of 300KCps to 500KCps. In order to jet, the flux must be heated so that its viscosity is decreased to about 20 Cps.

Three tests were performed to determine feasibility of the process utilizing picoliter flux dispensing. The first was the evaluation of droplet formation as a function of temperature and voltage. The second was quantitative evaluation of the tacky flux dot size and shape control. The third was the tackiness of the samples printed. The tacky flux used for the feasibility investigation is the one currently in use on the manufacturing floor.

EXPERIMENTS

"No Clean" Hot Bar Soldering Feasibility Test Procedures

No Clean Flux Characterization And Jetting Behavior. The flux vicosities were measured with a Brookfield LVT Viscometer, a UL adapter, and a EX 200 temperature bath combination. The surface tension measurements were taken with a Tensiomat Model 20, and a Autotensiomat fluid heater combination.

For each of the flux types, drop velocity and mass were measured as a function of frequency over the range of 2 to 5 KHz using the relation in Equation 1 and Equation 2. As a standard set-up condition the voltage to these devices was determined by jetting drops at 3 m/sec and 2 KHz.

Flux Printing Onto PWB. The impulse jet device was integrated to a precision positioning stage. The test board selected had four panels with one 15 mil pitch, 188 pin pad pattern on each panel. Each pad dimension was .1 inch by .008 inch. The system was debugged and wide line and fine line patterns at various frequencies were printed onto the substrate pad patterns. Only one of the "no clean" fluxes was used in this part of the testing. Both wide line and fine line printing was run on the test board pad patterns with a constant table velocity of 12.5 mm/sec. Faster velocities were available but were not used so that the flux printing could be observed in real time. In order to maintain the dispensing volume and achieve higher print speed both the table velocity and the jet frequency must be proportionally increased.

For the wide line pattern the dispensing target was the line parallel to the pad tips, and half way along the pad length. An upper frequency threshold of 1.21 KHz was possible before an excessive amount of flux flowed past the ends of the pads. The calculation of the average flux solids density deposited on each pad was .022 to .043 microgram/sq.in. This corresponds to the flux manufacturer's specification of 500 - 1500 microgram/sq.in. of solids. It is important to note the three orders of magnitude discrepency in the quantities of the solids ranges. However, it is also important to understand that the flux manufacturer determined this specification by the maximum solids density allowed for a no clean flux specification requirement rather than as the minimum density required for quality solder joints production.

For the fine line application on only the pads, the flux was dispensed along the length of each pad. An upper jetting frequency of 80 Hz was found before excess flux wetted past the pad edges. Calculation of the flux density on each pad showed .019 microgram/sq.in. and the same issues hold as in the wide line case cited above.

Hot Bar Soldering. Because the run time of the wide line dispensing pattern was about 30 times faster than that of the fine line dispensing pattern, the operation mode of choice would probably be wide line printing. Therefore, the hot bar solderability portion of the tests concentrated on the wide line flux dispensed boards. 15 mil pitch TAB parts were hot bar soldered using a Universal Instruments 4682B fine pitch bonder.

Acceptable joints were created by hot bar reflow when the pads were fluxed with a five pass wide line pattern, a table velocity of 12.5 mm/sec, and a jetting frequency of 1.21 KHz. The thermal profile parameters in this case were an idle temperature of 300 deg C, a melt temperature dwell at 300 deg C for 3 seconds, a lift off temperature of 140 deg C, and a force level of 6 Kgf on the hot bars.

Pull tests were done manually looking through a microscope and pulling each lead normally to the board surface with a minature hook. Acceptance criteria for the solder joints was for the lead material to break before the solder joint. Selected cross section samples of solder joints were prepared to assess joint quality.

Tacky Flux Feasibility Test Procedures

High Temperature Dispensing Test Stand. Figure 7 shows a schematic of the test stand, with the principal components listed in Table 1. A description follows.

The reservoir contains a supply of flux. A uniform temperature is maintained by submerging the reservoir of flux and all fluid lines in a heated bath. Glycerin was used for the constant temperature bath. The temperature of the bath is measured with a submerged thermocouple.

A custom fabricated heater sleeve slips over the outer diameter of the impulse jet (Figure 8). The heater consists of a brass sleeve that is 1 inch long, by .5 inch in diameter, and wrapped with insulated resistor wire. Because the device is small, constant temperature is difficult to maintain, so a temperature controller was added to the circuit. Temperature is measured with a thermocouple that is mounted inside the case of the impulse jet.

The impulse jet is mounted horizontally in order to facilitate the observation of droplet formation from above by microscope. An LED strobe, which is mounted below the orifice, illuminates the droplets as they are formed.

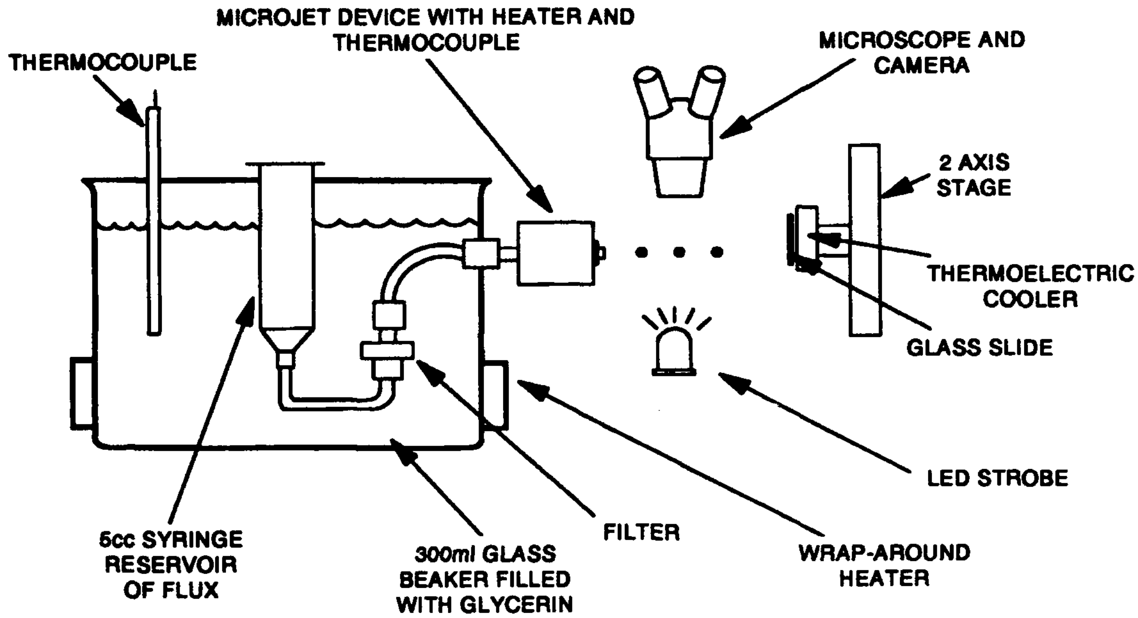

FIGURE 7. Schematic of the Test Stand.

TABLE 1. Principal Components of Test Stand.

Component	Description
Temperature controller	Omega CN9000
Device heater	Custom fabricated
Bath heater	Omega Flexible Electric Heating Tape, Cat. No. FGS051-020
Two axis stage	Oriel Stepper Mike 18503
Motor controller	Oriel model 20010 2 axis stepper motor driver with RS-232 interface
Microscope	Olympus SZH
Camera	Sony DXC-107
Power supplies	
bath heater	Staco type 3PN1010 variable transformer
device heater	Bruelle Instruments 1030
Signal generation	
frequency source	HP3314A
pulse generator	Tektronix type 115
amplifier	Kron-Hite 7500

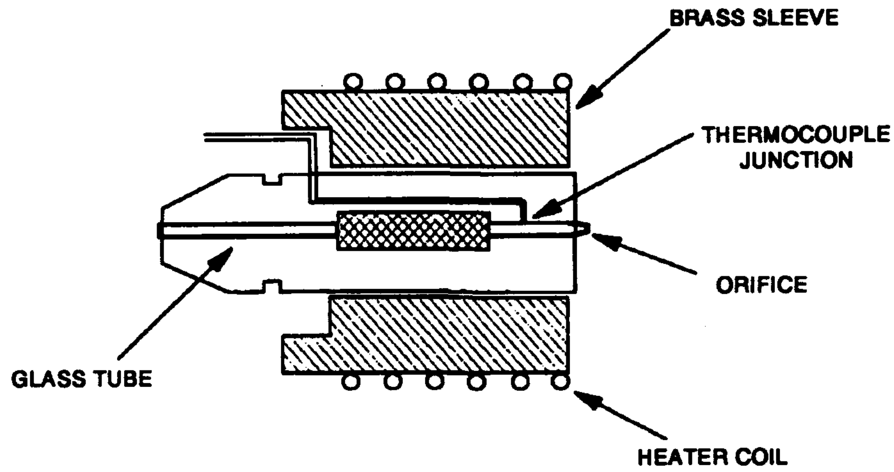

FIGURE 8. Schematic of the Impulse Jet Device, Heater, and Thermocoupl

The droplets strike targets that are mounted on a two axis stage. The stage can be removed easily for maintenance of the impulse jet or for an unobstructed view of droplet formation. Motion of the stage and initiation of the droplets are controlled by a PC-compatible computer.

Tacky Flux Characterization and Jetting Behavior. The flux, X1, specified for this study was one currently in use as a tacky flux. A less viscous version, X2, and X3 were also created and tested. The velocity and size of the droplets are functions of the fluid properties. The high viscosity of the tacky flux, which is the fluid property that inhibits droplet formation in this application, can be lowered by heating.

Viscosity measurements versus temperature were made with a Brookfield model LTV viscometer while the flux samples were submerged in a Brookfield model EX-200 constant temperature bath.

Droplet formation was observed using the test stand described above. First, a dispensing device was installed. Then, flux was liquified by partially submerging a container of flux in hot water (70-80°C), and the flux was poured into the reservoir. Next, the heaters were turned on, and the temperature was allowed to stabilize before generating the droplets. The distance between droplets was measured optically with a calibrated filar objective on the microscope. The droplet weight was measured by weighing the fluid that was dispensed into a vial over a 2 minute interval.

Dot Size. A dot of flux consists of one or more droplets of flux dispensed at the same position on a substrate. Only the diluted X3 was used to form dots since drop formation with X1 and X2 was poor. Dots were created on a glass microscope slide using the test stand. The two-axis stage was positioned in front of the device, and a microscope slide was attached to a mounting fixture on the stage. The microscope slide was cooled to approximately 15°C with a thermoelectric device in order to prevent running of the hot flux since the target substrate was vertically oriented.

Movement of the stage and the signals to dispense droplets were controlled by a PC-compatible computer. An array of dots was created by indexing the stage between dispensing dots. Once the array was complete, the dots were examined under a microscope, and the outside diameters of the dots were measured using a calibrated filar objective.

Droplet weight was computed from the flow rate according to the procedure derived from the droplet formation tests. The weight of a dot is the product of the weight of the droplet times the number of droplets in that dot. The volume of the dot is the weight of the droplet divided by the density of the flux. An average height was computed by dividing the volume by the cross sectional area, $(\pi \div 4) \times \text{diameter}^2$.

Tackiness Testing

Tackiness data was collected on samples of both picoliter dispensed and stencil printed tacky flux.

The stenciled tackiness data was collected according to the procedure described in IPC-SP-819. The picoliter dispensed flux tackiness data was collected in the same way as the stenciled data with the exception of the pattern of flux. The picoliter dispensed pattern was created as follows:

1) The stenciled patterns of X2 were weighed (0.012 grams).

2) Since the X3 was thinner than the X2, and since much of the thinner was likely to bleed away, the weight of diluted flux was increased to obtain the 0.012 grams of undiluted flux ($0.012 \div 0.8 = 0.015$ grams).

3) The total number of droplets was determined by dividing the sample weight by the droplet weight (337,500 droplets).

4) An array of closely spaced picoliter dispensed dots was substituted for the IPC standard 0.25 inch diameter stenciled area. The 15 x 15 array of dots (225 total dots) formed a 0.25 x 0.25 inch square of flux. Each dot of picoliter dispensed flux consisted of enough dropletss to get the required total number of dropletss (total number of droplets ÷ 225 dots).

Tackiness was measured 2 minutes and 2 hours after the samples were complete. The samples were also weighed in order to verify proper application of flux.

RESULTS

"No Clean" Hot Bar Soldering Feasibility Work

Fluid Characterization. Three fluxes, L1, L2, and L3 were evaluated in the jetting characterization portion of the study. Viscosity and surface tension were measured over the temperature range of 15-45°C. Three measurements were made at each temperature. Because of the similarity of the results, the temperature range for the L3 flux was abbreviated. The results are shown in Figure 9 and Figure 10.

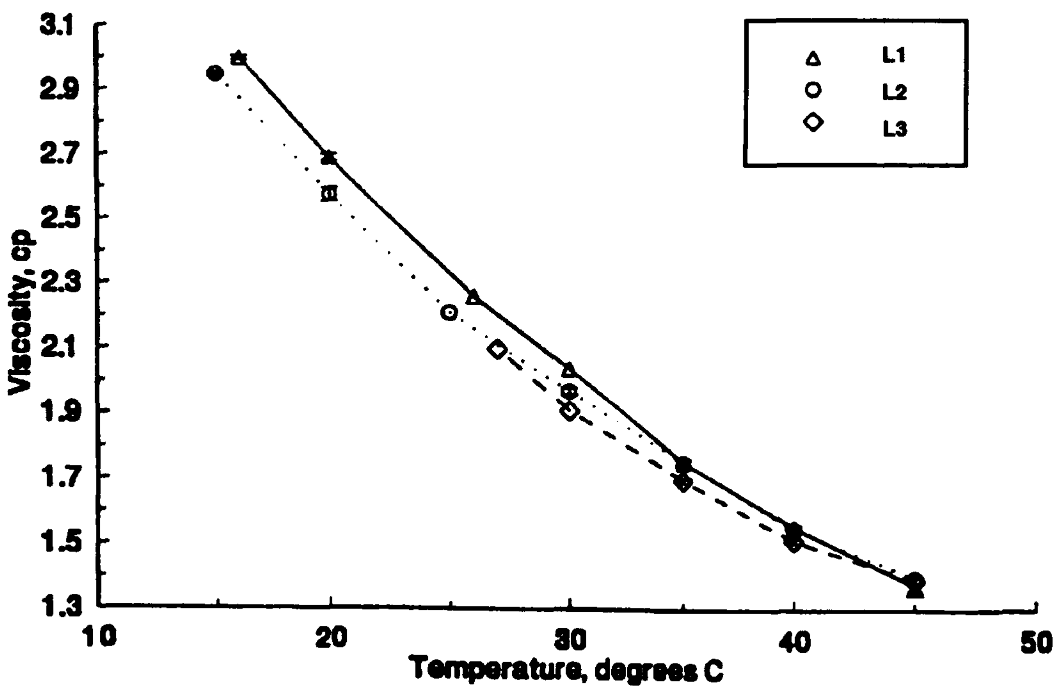

FIGURE 9. Flux Viscosity vs. Temperature of the Alcohol Based Fluxes.

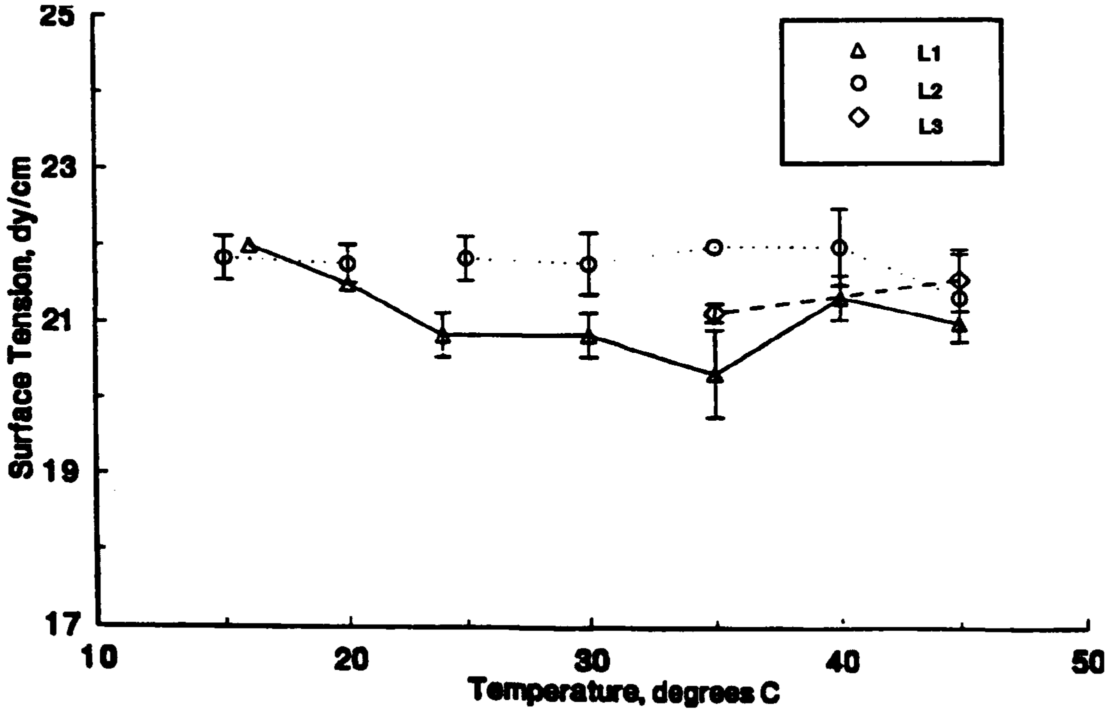

FIGURE 10. Flux Surface Tension vs. Temperatureof the Alcohol Based Fluxes.

Jetting Behavior. All three fluxes were evaluated for droplet formation behavior with a picoliter dispensing device, which has an orifice diameter of 53.2 microns. The voltage required to produce 3m/s at 2kHz was determined for all three fluxes, and the droplet velocity and mass flow at 2.5, 3, 4, and 5kHz were measured. The results are shown in Table 2 thru Table 4. For all frequencies tested the droplet formation observed, was adequate for the the fine and wide line printing.

TABLE 2. Droplet Formation Characteristics, L1 Flux.

Frequency kHz	Mass Flow mg/min	Droplet Velocity m/s	Droplet Volume pl
2.0	8.8	3.00	92.3
2.5	11.7	2.69	98.3
3.0	13.2	3.08	92.8
4.0	18.7	3.00	98.6
5.0	26.0	2.50	109.5

TABLE 3. Droplet Formation Characteristics, L2 Flux.

Frequency kHz	Mass Flow mg/min	Droplet Velocity m/s	Droplet Volume pl
2.0	7.3	3.10	75.5
2.5	10.0	3.72	83.3
3.0	11.7	3.30	81.3
4.0	15.9	2.90	82.8
5.0	24.0	3.06	100.0

TABLE 4. Droplet Formation Characteristics, L3 Flux.

Frequency kHz	Mass Flow mg/min	Droplet Velocity m/s	Droplet Volume pl
2.0	7.9	3.10	81.3
2.5	9.3	3.28	76.1
3.0	14.0	3.68	96.0
4.0	17.4	3.20	89.2
5.0	23.3	3.13	95.7

During the initial testing with the L1 flux, some buildup of solids around the tip of the device was observed. To get an idea of the run time before this buildup causes a failure, two 1 hour run tests were performed. For the first test, the jet was turned on every 2 seconds and 1000 droplets were dispensed at 2kHz. Thus, the jet was on for 0.5 second and off for 1.5 seconds. The buildup of solids on the tip was continual during the one hour test period, but the operation of the jet was unaffected. After completion of the test, the tip of the device was rinsed with isopropanol (the solvent for this flux), which immediately removed the solids buildup. The device was retested after cleaning and the droplet formation behavior was the same as previously observed. The second test was similar to the first, except that bursts of 1900 droplets were dispensed at 5kHz. This translates to a 0.38 second on time and

a 1.62 second off time. Again, the device ran for an hour with no degradation in performance. Cleaning the tip afterwards did not change the droplet formation behavior.

Flux Printing Onto Circuit Substrate. Both wide line and fine line printing were run on the test board pad patterns using a constant table velocity of 12.5 mm/sec. This allowed the flux printing process to be observed in real time. Higher print speeds at the same dispensing volume can be attained by increasing both the table velocity and the jet frequency proportionately. The fine line printing required dispensing on the pads only. This was achieved by applying the flux along the length of the pad. An upper limit for the jetting frequency of 80 Hz was achieved before excess flux wetted past the pad edges.

For the wide line printing the dispensing target was the center line between the ends of the pads. An upper jet frequency limit of 1.21 KHz was possible before excessive flux flowed past the ends of the pads. Upon printing multiple pass, wide line patterns the solids deposited seemed to be uneven along any one pad surface. From the pad center to +/-.038 mm along the length ends of the pads little solids was visible to the naked eye. While from +/-.038 mm along the length ends of the pads a heavy build up of solids was visible but gradually disappeared in concentration at the ends of the pads.

Hot Bar Soldering. Figure 11 shows the solder joint cross section of the heel and toe after hot bar bonding and pull testing. Flux had been dispensed with one wide line type pass at a table speed of 12.5 mm/sec and at a jetting frequency of 1 KHz. Solids density on the pads calculates to between .022 - .044 microgram/sq. in. The solder joints are poor to nonexistant due to the poor wetting of the solder to the lead. Vertical pull tests resulted in solder joints breaking before the lead material. Figure 12 shows the solder joint cross section of the heel and toe after hot bar bonding and pull testing. Flux had been dispensed with five wide line type passes at the same table speed and at a jetting frequency of 1.21 KHz. Solids density on the pads calculates to .11 - .22 microgram/sq. in. This solder joint appears dramatically superior in its fillet structure. Pull tests of these leads resulted in failure of the lead material before the solder joint. Solder joints formed when flux was applied in 2 to 4 passes of the wide line pattern were also evaluated. For the few parts tested joint reliability was questionable. It seemed that the process would require at least five passes for acceptable solder joint yields.

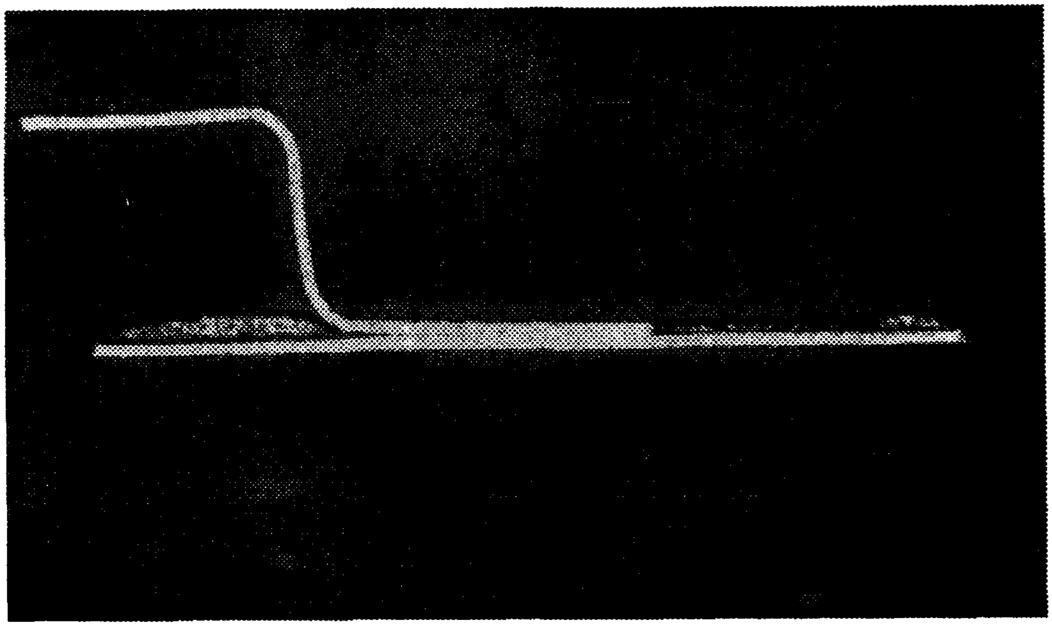

FIGURE 11. Solder Joint Cross Section of a Joint Created with Between .022 - .044 Microgram/sq. in. of Flux Activators.

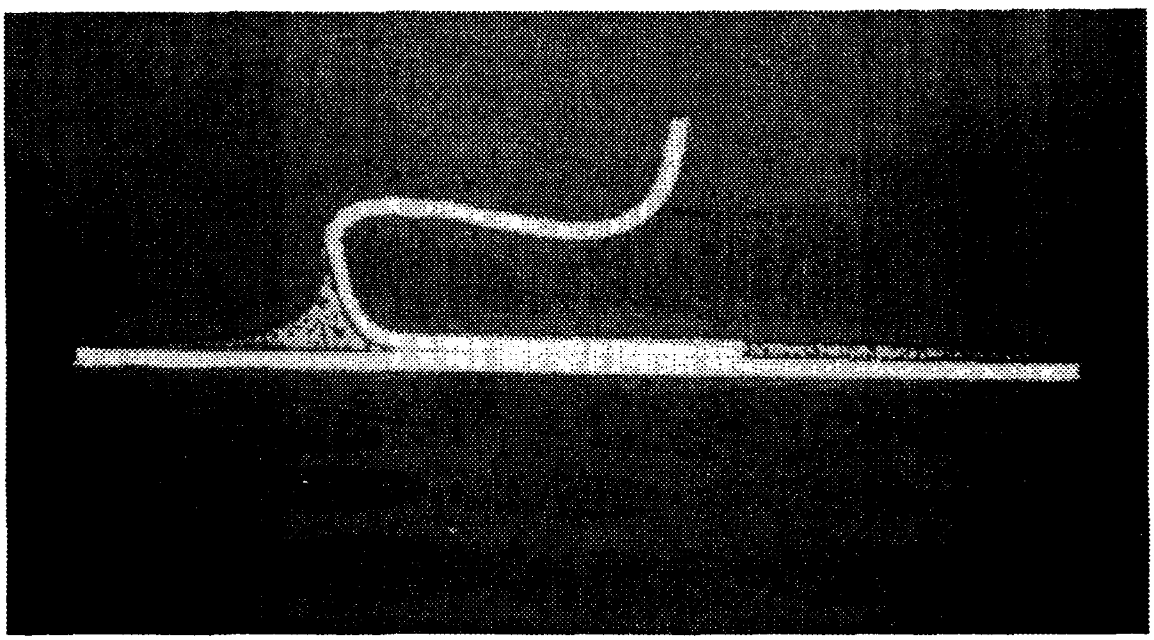

FIGURE 12. Solder Joint Cross Section of a Joint Created with Between .11 - .22 Microgram/sq. in. of Flux.

Tacky Flux Dispensing Feasibility Work

Tacky Flux Characterization and Jetting Behavior. The viscosity of X1, X2 and the diluted X3 near 100°C are shown in Table 5. As expected, the viscosity decreases with temperature. Viscosities of 1 to 20 centipoise are typical for picoliter dispensed fluids.

TABLE 5. Viscosity of X Type Fluxes Near 100°C

Temperature, °C	Viscosity, Cps X1	Viscosity, Cps X2	Viscosity,Cps X3
75	110	51	11
80	85	38	8
85	63	28	6.5
90	46	19	5.2
95	40	16	-
100	30	14	-

Velocity versus temperature for the X3 flux is shown in Table 6. This data was collected with a single dispensing device operating at 2000 drops/sec. The same device was used to dispense the X2 at 100°C and 2000 drops/sec. The velocity was nominally 1 meter/sec at a pulse voltage of 100 volts. The actual velocity for unknown reasons fluctuated by about ±0.5 m/s. Drops did not form at temperatures less than 100°C with the X2 flux. None of the available picoliter fluid devices would form drops of X1 flux at temperatures up to 120°C and pulsing with voltages up to 100 volts.

TABLE 6. Viscosity-Temperature Data for the X3 Flux

Temperature,°C	Velocity, m/s	Pulse Voltage
70	1.5	75
80	1.5	60
90	1.5	50
100	3	50

Dot Size. The dot size versus number of droplets is shown in Table 7. These dots were created using a single device operating at 3000 drops/s. The pulse voltage was 45 volts. Flow rate was 14 mg/min, so the average drop weight was 7.8 x 10^{-8} gm/drop. The device temperature was held at 100°C, the reservoir temperature at 65°C, and the target was cooled to 15°C. The diameter and height of the dots cannot be directly controlled, but the amount of flux that is dispensed can be controlled. The numbers in Table 7 indicate expected dot size for a given amount of flux. The diameter and average dot height are likely to change if the flux or dispensing conditions change.

The drop height could not be measured directly. Instead, the average height was computed form the volume of the number of drops that were dispensed. The computed average height of the dots is a conservative estimate of the height. Since the drops are somewhat hemispherical (not cylindrical) in shape, the actual maximum height of the dot is greater than the average height shown in Table 7.

TABLE 7. Dot Diameter Versus Number of Droplets for the X3 Flux.

Number of Droplets	Dot Diameter, mm	Average Dot Height Microns
1	.15	23
2	.175	36
5	.25	41
10	.3	58
20	.35	86
50	.5	104

Tackiness Testing. Tackiness forces are shown in Table 8. In general, the picoliter dispensed patterns are less tacky than the X1 pattern. but the picoliter dispensed patterns were not as tacky as the stenciled X1. Photographs of the microdispensed patterns are shown in Figure 13 and Figure 14. The picoliter dispensed patterns are less tacky than the stenciled X1 pattern. Whether the picoliter dispensed flux is tacky enough or not can be answered more definitively once the minimum required forces are known.

TABLE 8. Tackiness Test Data

Method/flux	After 2 Minutes		After 2 Hours	
	Ave Force g	Ave weight mg	Ave Force g	Ave Weight mg
X1	138	14.6	84	18.6
X2	50.1	11.7	47.4	11.5
X3	150	11.9	172	12.1

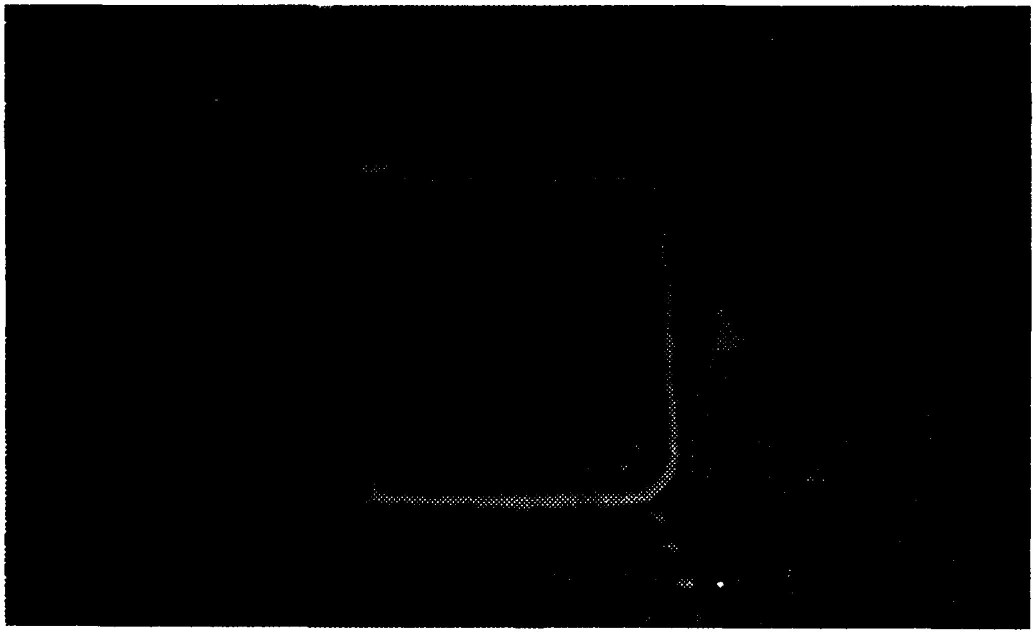

FIGURE 13. Picoliter Dispensed Tackiness Test Pattern.

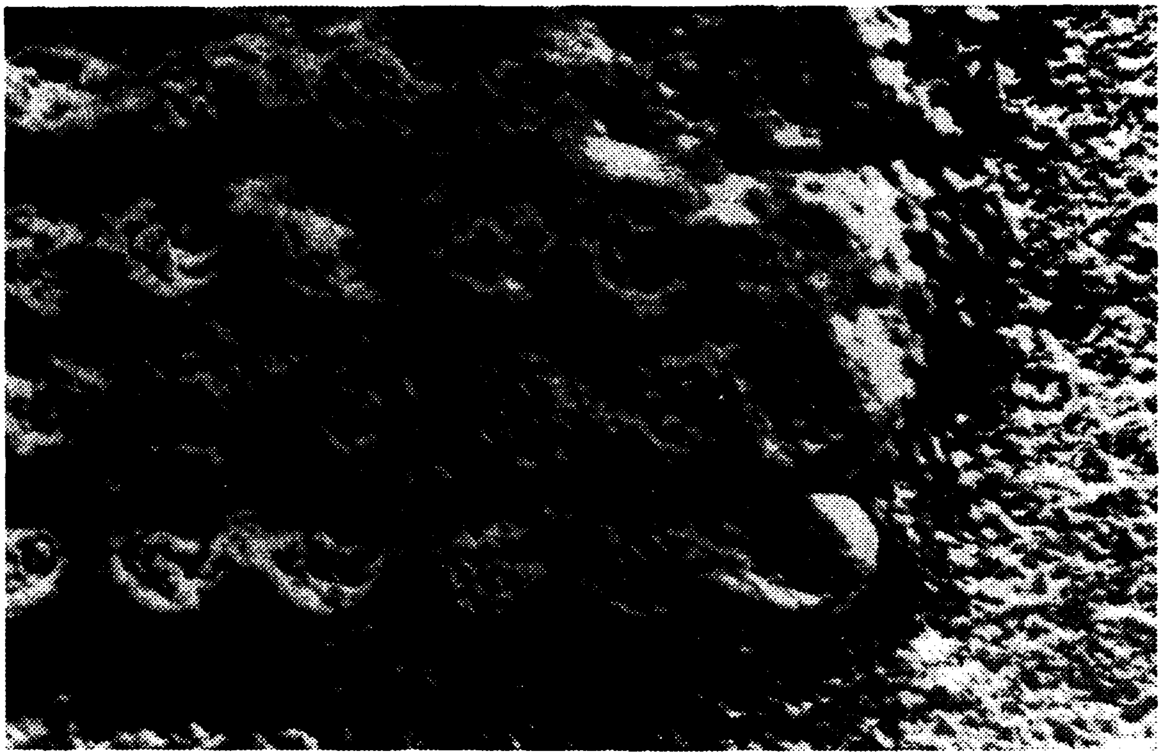

FIGURE 14. Detail of Picoliter Dispensed Tackiness Test Pattern.

Conclusions

"No Clean" Hot Bar Soldering Feasibility

Fluid properties measurements indicate that the three "no clean", alcohol based fluxes should behave acceptably in the described picoliter dispensing device. The viscosity measurements indicate that droplet formation behavior would be better at lower temperature, but, because of the simple pattern to be printed, the behavior at 25-35°C is acceptable. Surface tension is effectively invariant with temperature.

The droplet stream behavior of the flux suggests that these three fluxes are suitable for wide and fine line printing onto 15 mil pitch pad patterns. Under the jetting conditions simulating manufacturing conditions, the time between orifice tip cleaning is more than one hour.

The hot bar soldering tests indicate that picoliter flux dispensing can deliver .11 - .22 microgram/sq. in. of solid activators on a pad, and can acheive good solder joint wetting. The amount of solids is so small, it more than satisfies the flux manufacturer's recommended figure of 500 to 1500 microgram/sq. in. Therefore, by applying picoliter flux dispensing, the feasibility of a "no clean" hot bar soldering process for ultra fine pitch components has been demonstrated.

Tacky Flux Dispensing Feasibility. Heating X type tacky flux above 80°C lowers their viscosity to the point where it can be jetted with the described picoliter dispensing device. Although no jetting was observed with the X1 flux, and minimal jetting capability was observed with the X2 flux, device improvements should change this. The X3 flux jetted uniformly enough for the application of creating controlled sizes of tacky flux dots. The tackiness test results show that the picoliter dispersed X3 flux has about the same order of tackiness as the stenciled X1 flux. As to whether the picoliter dispensed X3 flux has definitly enough tackiness, or whether the X1 and X2 fluxes must be utilized for acceptable tackiness results, remains to be seen. However, by applying picoliter flux dispensing, feasibility of an ultra fine pitch mass reflow soldering with tacky flux process has been demonstrated.

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POLLUTION CONTROL AND HAZARDOUS MATERIALS MINIMIZATION IN A PRINTED WIRING BOARD SHOP: A CASE STUDY

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ABSTRACT

This case study contains information on the methods used by the Electronics Prototype Section to protect personnel and the environment from the hazardous materials used to fabricate printed wiring boards. Discussed herein are the past business practices, the era of awareness, the development of new business practices, and future plans for protection of the environment. Also mentioned are the problems encountered during installation of the wastewater treatment system.

INTRODUCTION

The fabrication of printed wiring boards (PWB) involves a variety of different processes that are divided into two categories: dry and wet fabrication. Dry fabrication is composed of operations such as drilling, routing, and imaging; whereas wet fabrication is composed of scrubbing, developing, plating, and etching. This study focuses only on the wet processes and the associated problems relative to environmental stewardship.

Most, if not all, of the chemicals involved in wet processing are hazardous to some degree. These hazards revolve around the chemical properties used in processing. For example, strong mineral acids are extremely corrosive and strong acid vapors readily degrade most metals on contact. Inhalation of these vapors can cause a range of problems from slight respiratory irritation to pulmonary edema and death. All these hazards can be reduced or even eliminated from the work place by engineering controls and substitution. Engineering controls include personal protection equipment, proper ventilation, and

Standard Operating Procedures (SOP). Substitution consists of replacing hazardous materials with other less hazardous materials.

PAST OPERATION PRACTICES

PROCESSING

The plating processes of environmental concern were electroless copper deposition, electrolytic copper plating, and electrolytic tin/lead or solder plating. All of these plating shop rinses were tap water overflow and were discharged directly into an Industrial Sewer System (ISS). Due to a lack of knowledge and awareness, the initial flow rates of the rinse waters were approximately 2,000 gallons/hour during processing. Contained within this substantial rinse discharge were regulated materials (i.e., copper, tin, lead, and formaldehyde).

Scrubbing and deburring equipment used to process PWB panels was plumbed to discharge directly into the ISS. This discharge was approximately 12 gallons/minute. The effluent from this process contained copper particles along with fibrous material from the scrubber wheels.

The photoresist developer and stripper used in the imaging process were also plumbed to discharge directly into the ISS with approximately 6 gallons/minute of outflow. Alkaline effluent in the imaging process contained residual organic material in solution and suspension.

Conveyorized spray etching equipment used to removed unwanted copper was plumbed to discharge directly into the ISS. Outflow was approximately 12 gallons/minute from each. Effluent from etchers contained copper, hexavalent chromium, and ammonium ion. There were both acidic and alkaline waste solutions contained in the effluent.

The clean/neutralization line used in support of the Hot Air Solder Leveling (HASL) process was plumbed to discharge directly to the ISS. Outflow was approximately 6 gallons/minute. Effluent from this procedure contained residual organic compounds as well as tin/lead solder particles.

As can be seen from the aforementioned situations, this shop had much to learn about environmental responsibility and natural resource conservation. This situation was not a deliberate "nose-thumbing" attitude toward the environment and natural resources; but rather it was brought about by lack of knowledge and awareness.

PROCESS CONTROLS

Control over the parameters that govern the effectiveness and efficiency of a process was important to the quality of the product being fabricated. The extent to which a process should be controlled was determined by various factors with cost being the most critical factor. Too little or too much money invested in process control resulted in higher operating costs. Too little money invested resulted in production of marginal and scrap products; while too much money resulted in no return from the extra investment. A proper balance between these two extremes had to be achieved to maximize benefits while minimizing operational costs.

Control of plating processes was monitored by titration and Hull Cell analysis. There were problems associated with titrations (e.g., variable endpoint determination). An example of one such variable was the presence of an entity that interfered with the endpoint determination. A Hull Cell is simply a small electroplating tank that was designed specifically to analyze electroplating baths. This apparatus enabled the analysis of all relevant current density areas on a single-cell panel. The appearance of the panel indicated the condition of the bath and its components. However, this analysis did not produce any quantitative data on which to base a decision as to what corrective action was required.

Application of these process controls for plating necessitated frequent dumping (every 6 to 8 weeks) of the various process baths. This was done to prevent the "crash" of the process resulting from the build-up of constituents that may have had deleterious effects on this procedure. Continual renewal of the plating chemistry required the procurement and storage of a large amount of chemicals plus associated labor costs. It became apparent that these processes were costly--both monetarily and environmentally.

Control of photoresist developing was accomplished by adjusting the process time to compensate for the deterioration and dilution of

the developer chemistry. This developing process chemically "washed" unexposed imaging photopolymer from a panel by using an alkaline rinse. As the developer chemistry became saturated with unexposed photopolymer, the pH of the solution began to decrease. This decrease in pH caused a concomitant reduction in the effectiveness of the rinse solution. When PWBs were observed to have residues after processing, the processing speed was reduced until the residues disappeared. When the performance of the process was determined to be unacceptable, either an addition was made to rejuvenate the solution or the developer chemistry was discarded. Control of the photoresist stripping process was accomplished in the same manner.

Temperature control was a critical parameter in many of the steps involved in fabricating PWBs. Maintaining predetermined temperature parameters was accomplished with tap water circulation. All of the cooling water was discharged to the ISS. There was no recycling practiced. The etchers, developer, lamination press, and vapor degreasers required tap water cooling to control the temperature. During normal operations, approximately 8,000 gallons of noncontact cooling water was used weekly. Usage would fluctuate depending on the temperature of the ground water.

HAZARDOUS MATERIALS

Materials used in the wet fabrication processes are hazardous. The chemicals employed can be categorized into three groups: oxidizers, corrosives, and toxins.

Oxidizers are materials that readily oxidize substances with which they come into contact. An example is chlorine gas, which was used to regenerate an etching system. The etchant was chemically reduced as copper was removed from the PWB panel. Chlorine gas was used to reoxidize the etchant and restore etching ability.

Corrosive materials included acids, bases, and halogens. Each of these materials could cause corrosion on substances with which they come into contact. An example of this is the effect that strong mineral acids and their vapors have on metals and respiratory systems that were discussed at the beginning of this paper.

Toxic materials, irritants, carcinogens, and asphyxiants have an adverse effect on humans. Most chemicals used in the fabrication of

PWBs possessed one or more of these undesirable properties. Since there was a great concern for protecting the personnel exposed to these substances, it was extremely important that the personal protection equipment (PPE) be properly used.

The solution employed to etch copper without destroying the tin/lead plated pattern was chrome trioxide and sulfuric acid. The etching solution was heated to 120°F in a conveyorized spray module and was used until spent. Waste products were then stored in drums, labeled, manifested, and sent to waste disposal. The main component, chrome trioxide, is a known carcinogen and exposure to this compound has been documented to cause lung cancer.

The solvent used to remove dryfilm photoresist was methylene chloride, a suspected carcinogen. Removal was accomplished by placing a large solvent-resistant tray in an open sink and adding solvent. A number of panels were then placed in the solution and allowed to soak for several minutes. During this dwell time, the photoresist blistered and floated free of the panel surface. The panels were then withdrawn from the tray and held under running water to rinse the residual solvent into the Domestic Sewer System (DSS).

A liquid photoimagable resist was used to fabricate fine line circuitry. This resist was a xylene-based material formulated with photosensitive compounds. The resist was applied by pumping the compound onto a set of rollers which, in turn, was deposited onto the panels being processed. After each use, the equipment had to be cleaned by wiping the soiled areas with xylene, a chemical suspected of damaging bone marrow, thus causing anemia.

A solution of ammonium persulfate and sulfuric acid was used as a microetchant to remove oxides and prepare the PWB panel surfaces prior to plating. This same solution was used to strip the electroless copper deposit from the processing baskets. Exposure to the fugitive emissions from this solution caused severe respiratory irritation that results in a gasping cough and nose bleed.

1,1,1-Trichloroethane was used as a cleaning solvent and developer in a drum vapor degreaser. It was very effective in removing rosin flux residue after tin/lead deposit reflow and was the only compound capable of developing an image on photosensitive aluminum. As with methylene chloride, this compound is an asphyxiant. Additionally, it has the potential to destroy the stratospheric ozone. Destruction of

the ozone layer is thought to increase the incidences of a number of health problems including skin cancer and cataracts.

Sn 63 tin/lead solder was used in the HASL process, as well as to thermally stress quality control coupons. Prior to each operation of the leveler, it was necessary to scrape the solder dross from the surface of the molten solder. Dross was put into cans for future disposal. Periodically, the solder had to be replaced due to the build-up of various contaminants. Spent solder pot dumpings were also put into cans for future disposal. Disposal consisted of either sending the material to a landfill or to salvage. Long-term exposure to lead solder can cause chronic lead poisoning; manifesting itself as kidney, liver, and nervous system damage; and digestive disorders.

ERA OF AWARENESS

PERSONNEL

Slowly and subtly a culture change occurred in this PWB shop. Interest developed in the materials being used and questions arose as to what effect these materials were having. This culture change redefined the way that personnel viewed health, safety, and responsibility.

ENVIRONMENT

This environmental awareness gave rise to questions and concerns about what was leaving the PWB shop and the subsequent effects on the environment. Direct observation illustrated that products from processing (e.g., acids, bases, metals, and organics) were being disposed into lined evaporative ponds. Bath dumps accounted for approximately 2400 gallons/year of chemistry that were being sent to waste disposal. From this PWB shop, hazardous waste was transported to the on-station Hazardous Materials Holding Site and then transported to San Diego where it was treated and the resultant sludge incinerated. Transportation and treatment of our waste carried a heavy price tag both financially and environmentally. 1,1,1-Trichloroethane, a volatile organic compound, emitted vapors during processing that were exhausted directly into the atmosphere. (As previously stated, this compound has the potential to destroy the stratospheric ozone.)

None of these processes were tailored around natural resource conservation. The waste of water was especially perplexing when considering that the facility is located in the California desert and that California is in a drought situation. A hard look was taken into operation practices.

ENVIRONMENTAL RESPONSIBILITY

PERSONNEL

The first step in becoming responsible was to protect personnel from hazardous materials. This was accomplished by education, substitution, and procedure development. Training sessions were held to familiarize personnel with the Material Safety Data Sheet (MSDS) format. Each MSDS was thoroughly covered in the training sessions and personnel learned the hazardous ingredients, health hazard data, first-aid procedures, special protection requirements, and special precautions regarding each material used in fabricating circuit boards. As the awareness of hazardous materials increased, it was arranged for a physician to observe the procedures in action. Afterward, the physician and personnel discussed industrial illness and health concerns.

All materials were closely examined to determine the viability of substitution. Information was obtained regarding necessary changes to the procedures, equipment modifications, spent material disposal, cost etc. Standard Operating Procedures were developed for all procedures and for the safe handling of hazardous material. Through writing these procedures, personnel were made aware of previously unknown unsafe practices. Procedures were written to guide personnel through the process and to reduce unnecessary exposure to the hazardous materials. Written guidelines allowed personnel to work more safely and gave the accompanying benefit of process improvement. Personnel took ownership for their own safety.

ENVIRONMENT

During the studies, is was discovered that the environment was being negatively impacted by the use of lined evaporation ponds, methods of waste disposal, use of ozone depleting chemicals, and waste of natural resources. It was apparent that the lined evaporation

ponds that contained the chemical rinses were not environmentally sound. For this reason, the Naval Air Weapons Station (NAWS), China Lake, California, was ordered to "Cease and Desist" discharges into the ponds on or before 1 October 1991. Drastic changes in business practices had to be made to comply with the order. An investigation was initiated to tentatively identify techniques and technologies that would allow the desired objectives to be met.

Training courses were attended to investigate the different technologies available for wastewater treatment/reuse to minimize or eliminate chemical discharge into the ponds. This education covered the scope of wastewater treatment from metal surface finishing applications to circuit board manufacture. All information was recorded and categorized for evaluation. A quasi-benchmarking study was performed to look at what industry was doing with regard to wastewater treatment. Various facilities were contacted and systems evaluated for their feasibility in the PWB shop. In each case, inquiries were made into operational safety, system effectiveness, system efficiency, maintenance, and operational cost. Additionally, facility managers were asked to be candid and reveal any shortcomings of their systems and how they were handled. This was crucial to minimize unexpected expenditures and problems after installation. Everyone contacted was open and extremely helpful in this information gathering effort.

With all the needed information at hand, the task of identifying the most appropriate techniques and technologies for pollution control was begun. This facility strived to obtain the most possible out of the system (e.g., waste minimization, resource conservation, and process improvement). The PWB shop believed that the expectations were realistic and the goals could be accomplished.

Not all of the material alternatives tried were acceptable. Additionally, some of the alternatives, metal precipitation for example, were nothing more than changing the physical state of the hazardous materials. Ultimately, this technique was deemed unacceptable because it would add more steps to the process and would still generate hazardous waste.

The next hurdle addressed was that of site modifications to accommodate the system components. Site modifications were defined as relocation of existing processes, existing plumbing, existing utilities, and any excavation to accommodate new plumbing and tanks.

A site assessment was performed to identify the types of modifications needed to install the required equipment. To accomplish this task, a worse-case scenario was visualized in which the majority of the existing equipment and plumbing had to be relocated. A floor plan of the relocated equipment and ancillary plumbing was drawn. The floor plan identified tentative locations for the system components with maximum allowable dimensions. These dimensions included a reasonable amount of space around the perimeter of the components for maintenance and safety requirements. Because of high cost, excavation for new storage tanks was not considered a viable alternative. The gathered information was combined into a data package and the procurement phase was initiated.

Hazardous waste disposal was the next area addressed. As previously stated, bath dumps were drummed, labeled, manifested, and sent off-station for disposal. Costs of transportation and disposal of hazardous material were enormous. Also there was the liability issue associated with the disposed hazardous materials to be considered, since this facility was responsible for any damage done to the environment by the hazardous materials generated. This responsibility began at the time the material was generated and continued indefinitely.

A more efficient method to control the plating procedures was researched. Analytical methods were researched to provide a method to both identify and quantify all species in the plating bath. A capability of this type would drastically reduce the amount of hazardous waste requiring disposal. Obviously, a reduction in waste brought a concomitant reduction in operating cost and liability. A High Performance Ion Chromatograph (HPIC) was chosen because it would meet and exceed the analytical requirements.

Another area addressed was that of using ozone depleting chemicals (ODC). This facility used 1,1,1-trichloroethane to remove rosin flux residues after fusion of tin/lead plated deposits and as a developer for photosensitive aluminum. This issue was easily resolved since there are several alternatives available to ODCs that were suited to this facility's needs. First, a rosin flux was replaced with a water-soluble flux. This eliminated the necessity of ODC solvent cleaning after fusing the tin/lead deposit. Next, the photosensitive aluminum which required solvent-based developing was replaced by another material which was developed with an aqueous-based chemistry. Only one liter of the new aqueous-based developer was used in a system that

operated at room temperature. This is in contrast to 25 gallons of solvent that were necessary to develop the old material at 165°F.

Natural resource conservation was the next area addressed. With simple plumbing modifications to the rinse tanks, overflow rinses were eliminated and countercurrent rinsing was incorporated. In countercurrent rinsing, the water flows from one rinse tank to another against production flow. As the water cascades against the production flow, contaminants are carried away from the critical process baths. Contaminant drag-in was also eliminated. Water reaching the end of the line was treated and discharged into the ISS.

Rather than directing the treated water to the sewer, it was possible to close the loop and recycle the water. Installation of the Wastewater Treatment System (WWTS) provided a very efficient conservation system (see Figure 1). Additionally, flow restrictors were installed in the rinse water supply lines. These devices limited the flow of water to only 2 gallons per minute as compared to 15 1/2 gallons per minute prior to installation.

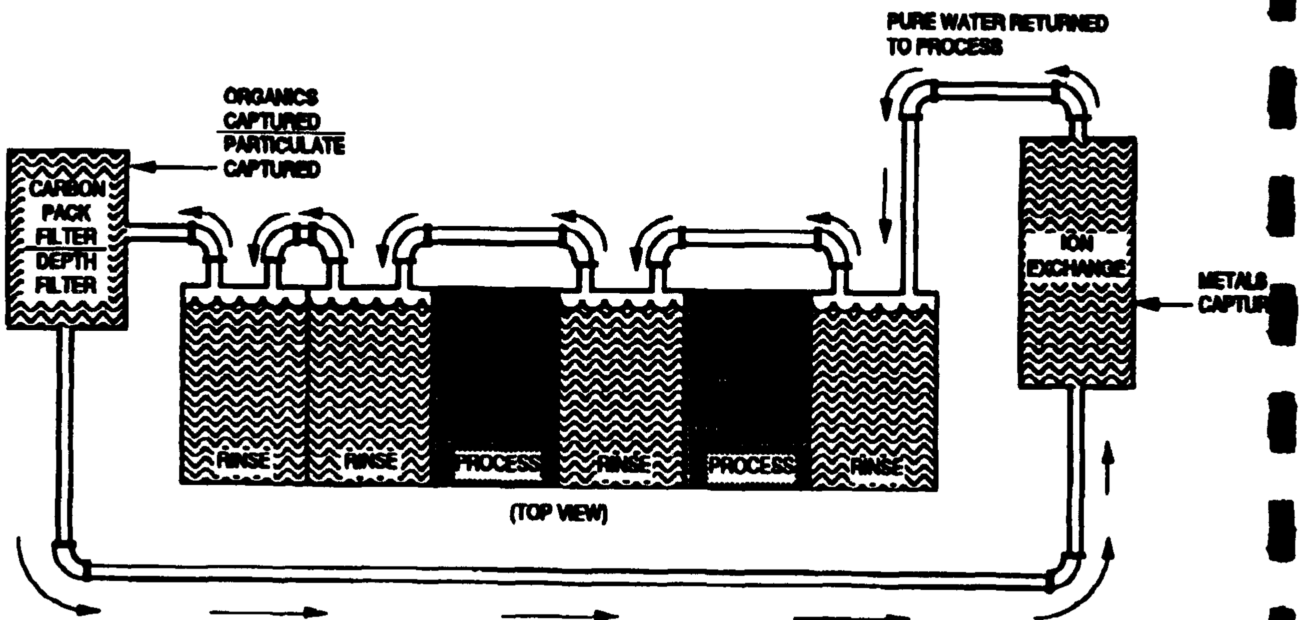


FIGURE 1. Countercurrent Closed-Loop Rinse System.

Finally, the cooling water issue was addressed. Research was performed to identify a method that would reduce or even eliminate the excessive outflow and still maintain control over the process temperature. A water chiller with a recirculating pump was identified as the solution to the problem. Prior to the installation of the water chiller, this facility was discharging approximately 8,000 gallons of water per week into the lined evaporative ponds. The water chiller provided better temperature control and eliminated any discharge into the ponds.

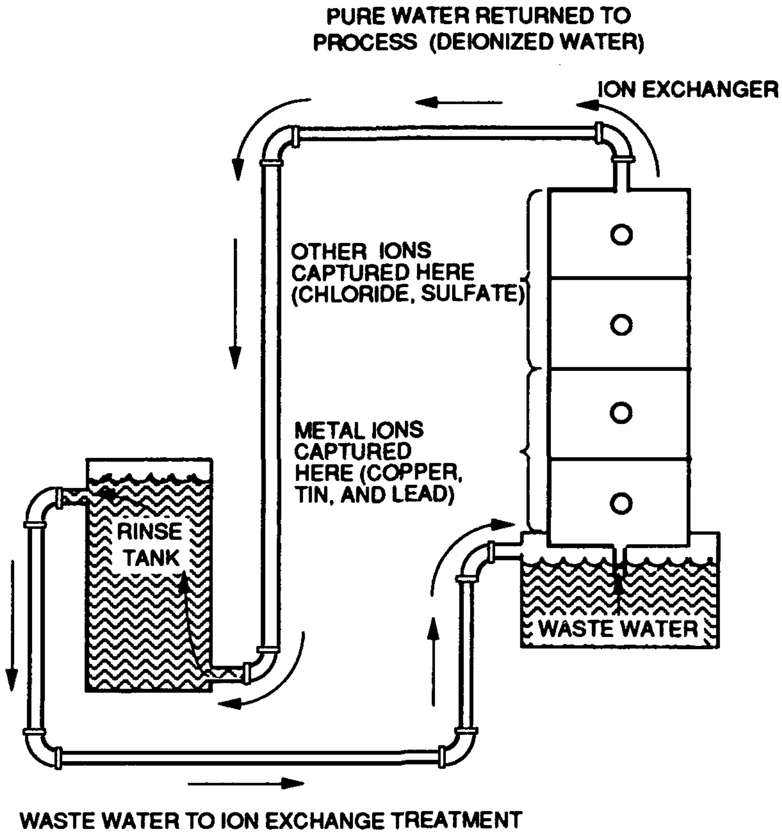
CURRENT OPERATION PRACTICES

WASTEWATER TREATMENT

Within the past few years, advances in ion exchange resins have opened the door to wastewater treatment. Ion exchange has been used extensively in water purification technology for many years.

The WWTS that was installed at this facility consisted of ion exchange, carbon pack filtration, depth filtration, bag filtration, electrolytic recovery, and pH adjustment. Each component was installed at the source of discharge throughout the shop. This reduced the plumbing and auxiliary transfer pumps that would have been required had the installation been centralized. As the wastewater flows through the resin system, contaminant ions are captured and replaced with hydrogen (H+) and hydroxyl (OH-) ions. The hydrogen and hydroxyl ions are then combined to form a molecule of water (see Figure 2).

During the ion exchange process, care must be taken that there are no oils or other types of organics in the water as these materials foul the exchange resins. Pretreatment is necessary to remove organic contaminants from the wastewater. This pretreatment is accomplished by carbon pack filtration. The carbon pack filters consists of a bag of activated carbon contained in a cannister. As wastewater is pumped through the filter bag the organic materials are adsorbed.



NOTE:
Closed loop for conservation and process improvement.

FIGURE 2. Ion Exchange Process.

The next treatment technology is depth filtration. This procedure removed suspended solids down to 5 microns. Depth filtration is necessary if treated water is to be reused. A build-up of suspended solids will interfere in the plating process, as well as clog the spray nozzles of other process equipment.

The last type of filtration incorporated into the WWTS is bag filtration. A bag filter is essentially a large sock. As the wastewater passes through the filter, particles are captured from the stream. The captured metal particles are then sold to offset some of the operational cost. The metals that are captured in this process are regulated and, therefore, justify the reclamation effort.

Upon ionic saturation of the ion exchange resin, the cannisters are physically transferred to a regeneration system for recovery of the

metal ions. This is accomplished by washing the resins with a dilute acid solution that releases the metal ions from the resin. These metal ions are then pumped into an electrolytic recovery cell for reduction to solid metals. Recovered metals are reclaimed and sold (offsetting the operational cost of the PWB shop (see Figure 3)). Cannisters containing other ions (e.g., chlorides and sulfates) are similarly washed, but with a dilute alkaline solution which is later neutralized for environmentally safe discharge into DSS.

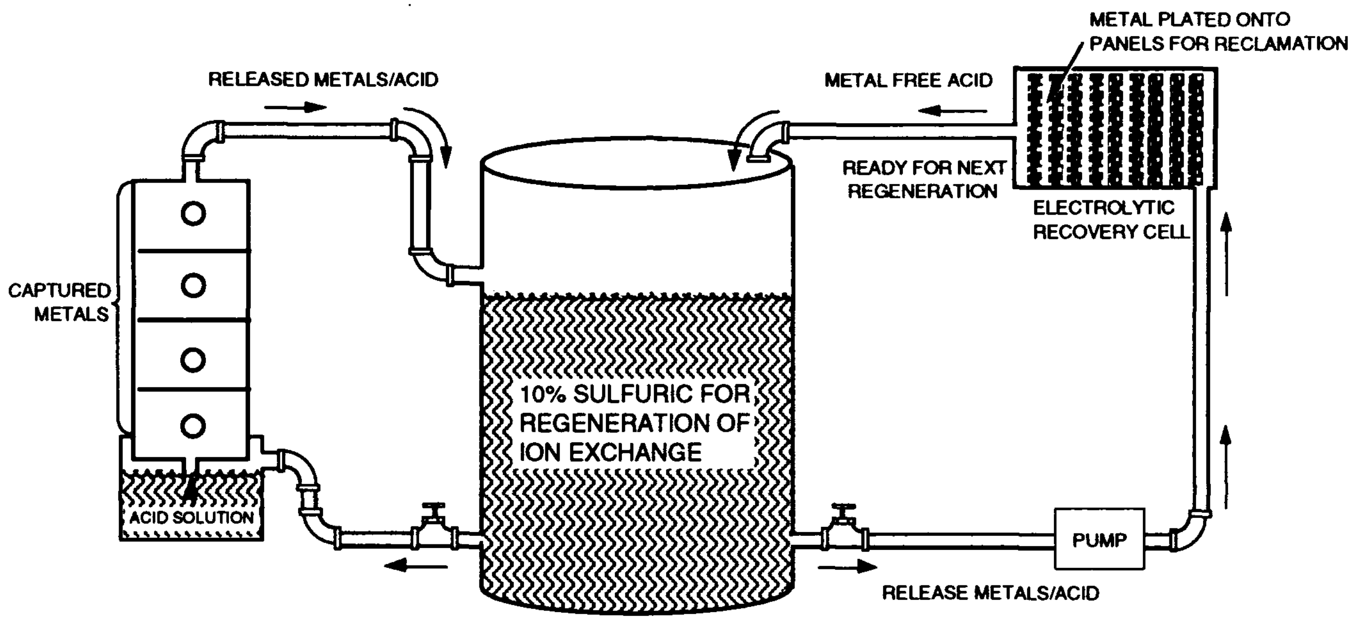
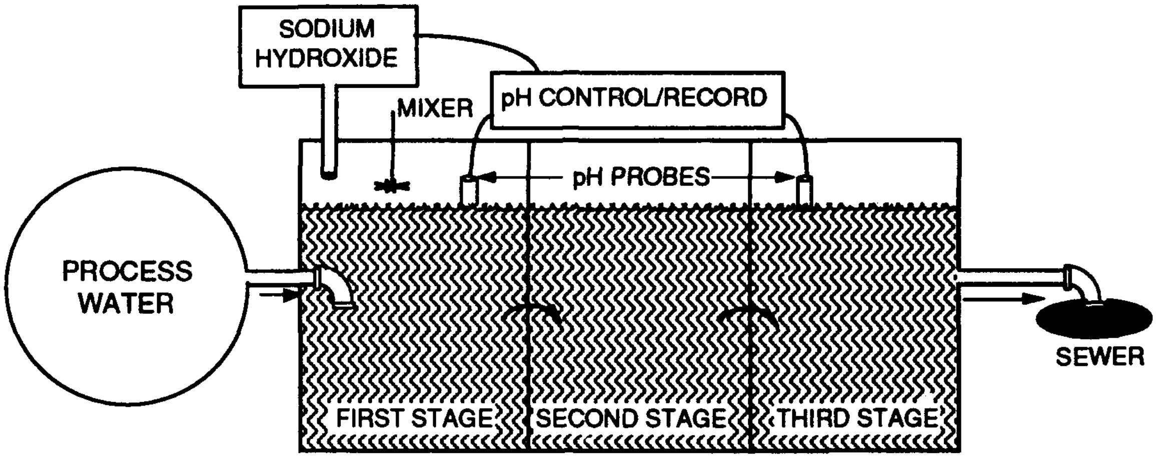


FIGURE 3. Metals Reclamation System.

The final step before discharge of the wastewater into the DSS is adjusting the pH. The shop's pH adjuster is a module consisting of three tanks with an attached control panel. Neutralization is accomplished by pH sensors, mixer, metering pump, alarm, and recorder (see Figure 4).



FIRST STAGE: WASTE WATER ENTERS SYSTEM. pH PROBE TURNS CONTROLLER ON WHICH ADDS HYDROXIDE FOR NEUTRALIZATION AND MIXES TANK.

SECOND STAGE: NEUTRALIZATION OF ACIDIC CHEMISTRY.

THIRD STAGE: pH RECORDED PRIOR TO DISCHARGE. ALARM SOUNDS IF pH IS WRONG FOR DISCHARGE.

FIGURE 4. pH Adjustment.

As the wastewater enters tank #1 of the module, the pH is measured. The controller then activates the metering pump which adds the pH adjusting chemical into the tank. The wastewater and pH adjusting solution are mixed together resulting in chemical neutralization. As more wastewater enters the tank for neutralization, the overflow runs into tank #2. This process continues and then overflows into tank #3. Located in the tank #3 is a pH probe that is connected to a recorder and alarms. The recorder maintains a hard-copy record of the pH at discharge into the DSS. Alarms will sound if the pH of the water does not meet the required value for discharge into the DSS.

The WWTS became fully operational on August 1, 1991, 2 months prior to the Cease and Desist order. All shop personnel have been trained in system operation and maintenance.

HAZARDOUS MATERIALS MINIMIZATION

A majority of the hazardous materials used have been substituted for materials that are less hazardous. This substitution directly affects the hazardous materials that are sent to disposal and also reduces the facility's operational costs. Some of the substitutions are

1. Chrome trioxide/sulfuric acid copper etchant was substituted with an ammonia based mixture. The replacement ammonia etchant removed the copper without effecting the tin/lead plated pattern. The etchant has no carcinogenic properties but does have an ammonia odor.

2. Methylene chloride photoresist stripper was replaced with a dilute solution of ethanolamine. A conveyorized photoresist stripping module was installed. Rather than standing over an open tray of methylene chloride, the process utilized an input conveyor in an enclosed system. Exposure occurred only during the replenishment of the chemistry and maintenance of the system. Hazards associated with the this substitute were slight respiratory and skin irritation.

3. Xylene-based photoimagable resist was substituted with a high resolution dryfilm photoresist. The dryfilm provides the same capability, but the hazards are greatly reduced. Since the lamination equipment is well ventilated, the only hazard is skin irritation.

4. The ammonium persulfate/sulfuric acid microetchant was replaced with a hydrogen peroxide/sulfuric acid solution. This replacement eliminates the severe respiratory hazards and allows the microetch system residue to be recycled. The solution is regenerated by chilling and allowing the copper to precipitate as the sulfate. After decanting and analysis, proper chemical additions are made to return the solution to optimum condition.

Recycling

Rather than send the SnPb solder pot dumpings and dross to salvage, this shop participates in an industry reclamation program. The reclamation program allows credit for scrap solder and dross, which offsets the shop's operational costs. The program sponsor provides the containers, manifests, labels, and pays for the cost of shipping to the refiner's facility. Refined materials are then sold at hardware stores for home-use soldering applications.

PROCESS CONTROL

Wet chemistry process control of all the bath chemistry was replaced with an HPIC. This instrument analyzes anions, cations, organics, and transition metals. The HPIC quantitatively identifies all chemical species contained in the baths. Data generated by this analysis is used in this facility's Statistical Process Control (SPC) program. In addition to the process bath analysis, HPIC is also used to analyze the contents of the wastewater before and after treatment. Quantities of hazardous waste sent to disposal are steadily declining while the quantities of material sent to reclamation are rising. The HPIC is a very powerful analytical tool that has made the dream of bath longevity into a reality.

Another control implemented was supplying each process line in the plating area with deionized water. Deionized water is used to generate new baths when necessary and to replace evaporation loss. This shop progressed from using four individual tap water lines to one line that feeds the deionizing system. Using deionized water dramatically improves the shop's plating processes.

Because bath temperatures are now controlled with recirculated chilled water, our processes are more efficient and natural resources are being conserved. No longer are 8,000 gallons of water per week being discharged to the sewer, but rather the water is continually being recycled.

The photoresist developer and stripper have had pH monitors installed. Chemical additions are dependent on solution pH, rather than on product attributes exiting from the systems. Although pH probes require frequent maintenance (e.g., filling and calibration), the extra effort is worthwhile as defects from the processes have been significantly reduced.

PROBLEMS ENCOUNTERED

There were only two significant problems encountered: etcher rinse water and scrubbing/deburring treatment.

1. Etcher rinse water. Analysis during the WWTS identification phase detected only traces of copper in the etcher rinse. For this reason, the rinse water was only pH adjusted and then discharged. Upon start-up of the system, the pH adjuster water became turbid. An analysis revealed that the turbidity was caused by a build up of precipitated copper hydroxide. The metal hydroxide was formed during the neutralization reaction of the wastewater. To eliminate this problem, the first-stage rinse water was passed through an ion exchanger to capture the copper ions prior to pH adjustment.

2. Scrubbing/deburring treatment. After two days of operation, the bag filter system would become filled with fiber from the scrubber wheel. Since this is a closed-loop system, the product from this process was coated with fiber. Contaminated panels are unfit for further processing. The solution to this problem was to increase the filtration capacity. Until a new filter manifold could be procured, a secondary bag filter was installed. This extended the time that the product from the process was acceptable to one week. To reduce unscheduled downtime, replacing the contaminated panels was placed on the "Weekly Maintenance Schedule".

FUTURE PLANS

Future plans for the Wastewater Treatment System is to continuously improve the system one small step at a time. Some examples of these plans are

1. Install solenoid actuated valves for inlet rinse. This improvement will allow us to run the rinses on certain tanks only when the process timers are operational.

2. Install pH controllers for the photoresist developer and stripper. This will fully automate the addition of replenishment chemistry.

3. Install a Close-loop system for the treated rinse on the developer and stripper. This would allow the reuse of water in the process.

The Environmental Project Office and this facility have been discussing controlling the shop's air emissions. The near-future goal is to accomplish similar achievements for air emissions that have been accomplished for waste water.

CONCLUSION

We believe that progress has been made. Presently, less hazardous materials are being used in a more environmentally conscious manner. The discharge of untreated wastewater has been eliminated and replaced with recycling of treated water. Archaic attempts at process control have given way to state of the art analytical methods. Waste of water for process cooling has been replaced with recirculated chilled water. Waste of process metals has been replaced with metals reclamation. Large quantities of hazardous waste for disposal has been drastically reduced. Attitudes of "that's the way we've always done it" have been replaced with attitudes of "how can we do it better". We have come a long way, but there is always room for improvement.

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SOLDERABILITY STUDY OF Sn/Pb ALLOY AFTER ARTIFICIAL AGEING BY ELECTROCHEMICAL REDUCTION ANALYSIS AND WETTING BALANCE TESTS

by

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ABSTRACT

Sequential electrochemical reduction analysis (SERA™) and the wetting balance test were used to assess the solderability of unaged and steam aged Sn/Pb electroplated Cu pins and through-holes. SERA™ tests of unaged Cu pins indicated the presence of a single Sn oxide, presumably SnO and the presence of two Sn oxide species, SnO and SnO_2, on the surface of unaged through-holes. SERA™ results of the two sample types in identical steam ageing environment showed that the oxide species formed on each sample type were similar to each other. After SERA™ testing all samples displayed a better surface solderability when compared with the surface condition before SERA™ testing. Experimental data obtained from both SERA™ and wetting balance test had similar qualitative results.

INTRODUCTION

A prominent part of the electronics industry is the formation of reliable solder joints between printed wiring boards (PWBs) and component leads. The term solderability is used by the industry to describe the total suitability of a component or a printed wiring board (PWB) for industrial soldering (Reference 1). Good solderability is defined as total wetting of molten solder to a base metal (References 1-4) which results in a solder joint that is mechanically strong and electrically conductive. Poor solderability results in a mechanically unstable solder joint which is subjected to rework, thus adding to production cost and decreased joint reliability (Reference 3).

Surface contamination of the base metal or component lead by the presence of metal oxides, oils and dirt is thought to be the primary cause in the loss of solderability (Reference 1). A more scientific method of measuring solderability is needed (Reference 5) and would help to identify solderability problems on the production floor.

A non-destructive, electrochemical analysis of solderability of PWB through-holes has been developed by Dr. Morgan Tench of Rockwell International Science Center, Thousand Oaks, CA. The analysis, known as sequential electrochemical reduction analysis (SERA™), measures the reduction in voltage potential of a through-hole when it is exposed to a reducing environment and a constant electrical current. We have compared SERA™ and wetting balance tests on Sn/Pb electroplated Cu needles and through-holes found in commercially manufactured PWBs before and after steam ageing.

EXPERIMENTAL METHOD

Two types of solder samples were used in this study. The first group of samples consisted of Cu pins that had previously been electroplated with Sn/Pb solder and the second group of samples consisted of through-holes that were found in commercially manufactured PWBs.

Electroplating of Cu Pins

Cu pins were made from bare copper wire that was 1.2 mm in diameter and cut into 30 mm lengths. Each individual pins was straightened and the tip rounded using coarse grit sandpaper. The pins were electrochemically plated with Sn/Pb solder and subsequently reflowed for 5 seconds in CuTech CGT-21B water soluble oil which was heated to 224-240°C.

Accelerated Ageing of Electroplated Pins and PWB Samples

The experiment was designed to test samples with different surface conditions due to solder oxidation and to compare experimental data between the two types of samples before and after steam ageing. To select an appropriate ageing time, a preliminary steam-ageing test was conducted. Both sample types were steam-aged in a Mountaingate Steam Ager at 87°C and 100% relative humidity (RH) for 8, 16 and 24 hours. Although the samples were exposed to the steam ageing for different times, their electrochemical reduction behavior and solder wetting properties could not be distinguished between the three ageing times. Therefore, the ageing times for the samples were reduced to 1, 2 and 3 hours.

Electrochemical Reduction Analysis (SERA™)

Electrochemical reduction analysis (SERA™) of the samples was performed on a prototype SERA™ apparatus in which a sodium borate buffer, pH of 8.4, was used as the electrolyte and purged with dry nitrogen gas. During the test, a constant reduction current (-20 $\mu A/cm^2$) was applied to a known area of the sample with the aid of a stainless steel counter electrode. The voltage potential of the samples vs a

SCE reference electrode was followed as a function of time. The chronopotentiograms obtained revealed the reduction of the surface oxides.

Wetting Balance Solderability Assessment

Solderability tests were done on a Multicore Universal Solderability Testing Machine. Due to the restriction of wetting balance testing method, only the electroplated Cu pins were used as samples. The following parameters were set for the wetting balance test: Range, 5g; depth, 7mm; speed, 20mm/s; duration, 5 sec; temperature, 235°C; solder, 63/37 Sn/Pb alloy; flux, Actiec 2 activated flux; minimum force change, 0.5 mN/mm; minimum correlation coefficient, 0.7; maximum soldering time, 0.8 sec.

RESULTS AND DISCUSSION

A characteristic of the chronopotentiograms for pin samples was the rapid drop in potential at the instant of applying reduction current (Figure 1, curve a). Then, the potential increases slightly toward a more positive value and sustains a constant voltage potential for a prolonged time, resulting in a broad plateau in the curve. The slight increase in voltage potential toward a more positive value and the occurrence of a plateau region was believed to be caused by a surface oxide reduction process. At the end of the reduction region, a rapid decrease of potential was observed. The presence of a single plateau in the reduction region of the curve indicates that only one oxide species, presumably SnO, was present and was reduced in the electrochemical process. For through-holes, the shape of the curve is slightly different (Figure 1, curve b). First, the potential gain back shortly after the reduction current was applied was more obvious and may be due to the fact that a thin, dense layer of more stable oxide was present on the through-hole surface. Second, the sample potential drops at a relatively faster rate in the reduction region of the curve, which may be an indication of a thinner oxide layer. Third, the reduction region contains two plateaus instead of one. It suggests that there were two oxide species present, presumably SnO and SnO_2, and both were reduced during the test. Finally, there was a consistent potential difference between the corresponding points on the reduction curves of pin samples and through-holes. We believe it was caused by the difference in electrical resistance of the electrolyte paths between working electrode and reference electrode when the working electrode was pins and through-holes, respectively. Overall, the characteristics of reduction curves indicate the types of oxide layers formed on two non-aged samples differed somewhat; the pins had a thicker, porous oxide layer of one species and the through-holes had a thin and relatively dense layer of two oxide species.

The sequential reduction curve for pins had a less obvious potential increase in

the voltage value at the beginning of the reduction process (Figure 2). The reduction region of the curve consisted of two plateaus, which indicated the reduction of two oxide species, in contrast to the single oxide present and reduced on the surface of unaged pins. From the potential range of the reduction region of the curve, we can assume that the oxide species present on the sample were mainly mixed Sn oxides. Since the second wave at a lower potential in the reduction region of the curve weighs more and has a longer tail, which lasts for more than 1050 seconds, steam-ageing seemed to facilitate the formation of higher tin oxides.

Similar changes in the shape of chronopotentiograms were observed for through-holes except that there was not a clear transition of one oxide reduction to another in the reduction region of the graph and the potential drops continuously until the baseline of the curve was reached (Figure 3). In addition, the reduction process lasted for about 600 seconds, which was longer than the pin sample under the same ageing treatment. Based on these observations, we may conclude that mixed tin oxide layers reside on the surface of the through-hole and the total thickness of these layers was thinner than those reduced on the surface of Cu needles electroplated with Sn/Pb solder.

The shape of the chronopotentiograms of both types of samples was similar. These curves show almost no voltage potential increase at the start of the oxide reduction process. A clearly defined transition point was not seen on the curves signifying reduction initiation of a different oxide species (Figs. 2 and 3). Compared with samples aged for a shorter time, the reduction portion of the curves lasted for a longer time period, indicating thicker mixed Sn oxide layers formed on the surface during prolonged exposure to the accelerating ageing environment.

To obtain statistically reliable results, tests on each sample type were repeated five times. Data shown in Table 1 were the average values taken from the parallel experiments.

From the listed values for various parameters measured and calculated in the wetting balance tests, we found the time constant becomes larger with the increase of sample ageing time, while the sample wetting force change becomes smaller when the sample ageing time was increased (Table 1). This means the speed and the strength of solder wetting decreases with the increase of ageing time. These were in accordance with the conclusions we made from earlier SERA™ experimental results. Contact angle at a given time was a measure of the extent of wetting, and data obtained for this parameter (Table 1) also showed that the extent of wetting decreased with prolonged sample ageing time.

Data for various parameters of the wetting balance test consistently proved that the SERA™ test had a good effect on solderability. This was a result of oxide reduction during SERA™ analysis and the presence of a cleaner and more solderable surface for soldering after a SERA™ test.

CONCLUSIONS

1. SERA™ experiments showed that there is only one Sn oxide species, presumably SnO, present in the surface layer of freshly prepared pin samples, whereas there are two Sn oxide species, presumably SnO and SnO_2, present on the inner surface of non-aged through-holes. Also, oxide layers on freshly prepared pins seem to be thicker than oxides naturally formed on through-holes.

2. Testing results of SERA™ indicated that in identical steam ageing environments, oxides formed on needle samples are similar to, but not exactly the same as those formed on through-holes. This may be due to the difference of the initial surface conditions between these two types of samples.

3. The chronopotentiograms obtained by the SERA™ test can predict the thickness and roughly determine the oxide species present in the oxide layers. For this reason, it provides a way to evaluate the surface condition and hence, the solderability of a sample being tested.

4. Experimental data obtained from SERA™ and wetting balance tests agree on a qualitative bases.

5. After SERA™ testing, samples displayed a better surface condition and solderability when compared with the condition of the surface before SERA™ tests.

6. With regard to the consistency of the testing results, the longer the steam ageing time of the samples, the less reproducible experimental data.

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Sample	Induction Time (sec)	Contact Angle at 3 sec	Time Constant (sec)	Correlation Coefficient	Dewetting (mN/mm)	Force Change (mN/mm)
Unaged	0.17	≤7	0.9317	-0.7900	0.006	0.757
Aged, 1 hr	0.20	≤53	1.5126	-0.7262	-0-	0.650
Aged, 1 hr*	0.12	≤4	1.4508	-0.6902	0.004	0.754
Aged, 2 hr	0.18	≤58	1.6222	-0.6654	-0-	0.614
Aged, 2 hr*	0.12	≤29	0.6468	-0.8328	-0.016	0.676
Aged, 3 hr	0.18	≤58	1.8994	-0.6036	-0-	0.622
Aged, 3 hr*	0.14	≤20	0.7984	-0.7702	0.028	0.708

*Wetting balance results of Sn/Pb Cu pins after the SERA™ test.

TABLE 1. Results of solderability assessment by wetting balance assay. Cu pins were electroplated with Sn/Pb solder and were steam aged for 1, 2, and 3 hours. Wetting balance analysis was conducted on the aged Cu pins before and after SERA™ testing.

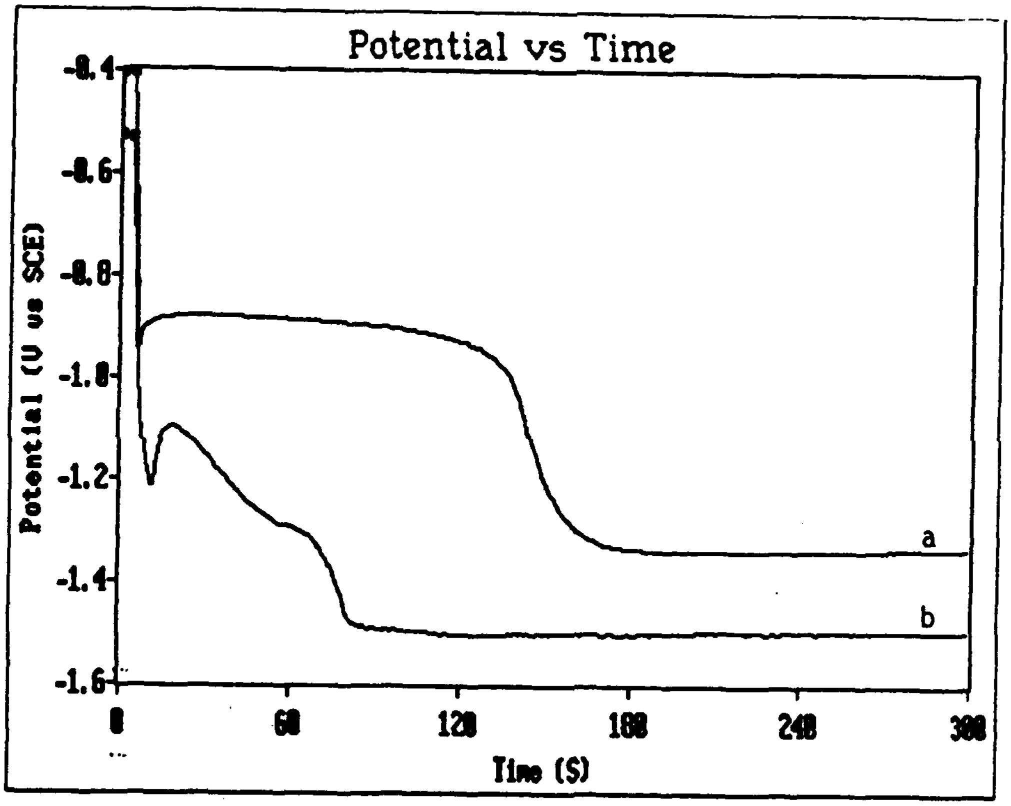

FIGURE 1. Reduction curves of unaged Cu pin electroplated with Sn/Pb solder alloy and commercially manufactured Sn/Pb plated through-holes. (a) reduction graph of unaged Cu pin and (b) reduction graph on unaged plated through-hole.

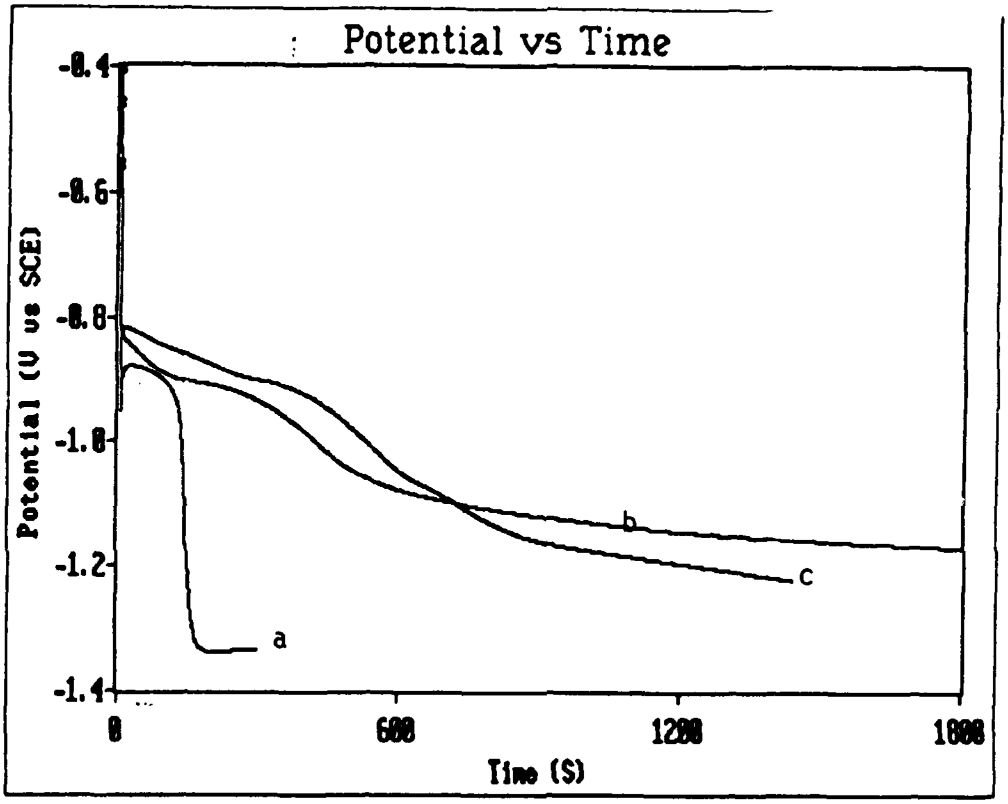

FIGURE 2. Reduction curves of unaged and steam aged Cu pins electroplated with Sn/Pb solder alloy. (a) reduction graph of unaged solder plated Cu pin, (b) reduction graph of solder plated Cu pin exposed to 87°C and 100% RH for 2 hrs and (c) reduction graph of solder plated Cu pin exposed to 87°C and 100% RH for 3 hrs.

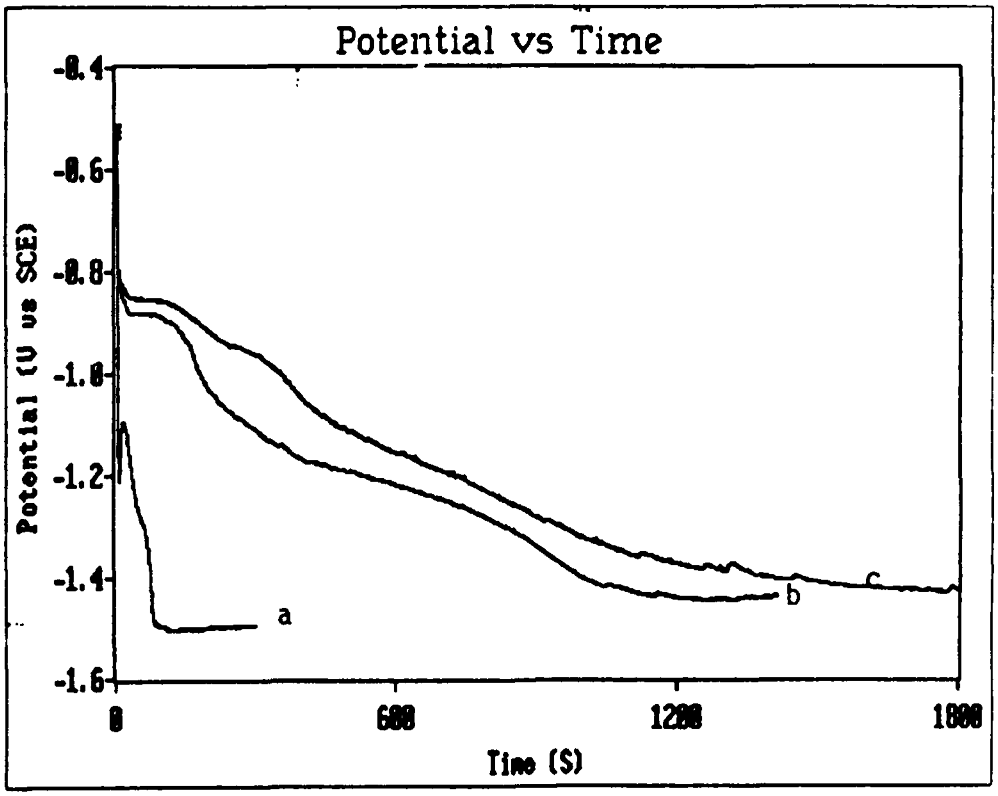

FIGURE 3. Reduction curves of unaged and steam aged plated through-holes. (a) reduction graph of unaged through-hole, (b) reduction graph of plated through-hole exposed to 87°C and 100% RH for 2 hrs and (c) reduction graph of plated through-hole exposed to 87°C and 100% RH for 3 hrs.

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INSPECTION WORK STATION FOR GRAPHICAL TRACKING AND ANALYSIS OF CIRCUIT CARD ASSEMBLY AND SOLDERING DEFECTS

by

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ABSTRACT

This article describes an integrated, graphics and database application in use at Northrop Corporation for inspection and quality tracking of Circuit Card Assemblies (Figure 1). The system permits factory floor users, namely, Production Inspectors and/or Operators, to automatically fill a database of product defect data through a graphical, point-and-click interface. Data collected includes Assembly Number and Serial Number, Defect Code, Category of Defect (Solder, Assembly, or Process Indicator per MIL-STD-2000), Component Reference Designator and Pin Number, Inspector's ID Number, Date and Time, Operation Number, and Inspection Occurrence.

Engineering and Management personnel may then retrieve information, formatted in numerous different ways and graphically presented, without a working knowledge of the database query language. Process Graphics include Line Graphs, Pareto Charts, and Control Charts. The graphics output, available online and in real time through fill-in-the-blank selection forms, is suitable for describing process status and, more importantly, for identifying, prioritizing, and solving process and product problems.

FIGURE 1. Production Inspector Using Inspection Work Station

SYSTEM OVERVIEW

A mouse-driven, graphical Inspection Work Station (IWS) has been developed for the Circuit Card Assembly (CCA) Production Inspection function at Northrop Corporation's Electronics Systems Division-Rolling Meadows (IL) Site. ESD-Rolling Meadows Site designs and manufactures complex electronic countermeasures (ECM) equipment to stringent military specifications, and as a DOD supplier, is required to track solder and assembly defects, rework defects per standard procedures, and provide closed-loop Corrective Action plans to address deficiencies in assembly and soldering processes. Where required by contract and applicable military

specification, Material Review Boards (MRBs) are expected to meet and reconcile assemblies having particular solder joints that require rework more than once. In all cases, inspection records must be maintained for use by Quality Assurance and on-site DOD inspection agencies.

The IWS and its associated central database provide these capabilities, completely online and in real time, without the use of paper. Over a dozen IWS stations have been deployed for Inspection operations in several work centers, networked to a host database server. Several stations are located in the rework areas, where inspection data is retrieved to indicate which component and solder joint locations require attention. Another dozen stations, located on the desks of Manufacturing Process Engineers and Managers, graphically display the inspection results to those responsible for process improvements.

The database server, a multiuser minicomputer, provides the IWS stations with CAD-generated graphical depictions of the CCAs to be inspected (called Defect Identification Drawings, or DIDs, see Figure 2 for an example), and maintains a table of defect records by CCA Serial Number.

Pre-programmed functions, available to the Inspector from pulldown and popup menus, permit the Inspector to instantly draw standardized defect marks and assign defect codes to locations as specific as individual solder joints. When finished, the system automatically fills database fields including the Assembly Number and Serial Number, Defect Code, Category of Defect (Solder, Assembly, or Process Indicator per MIL-STD-2000), Component Reference Designator and Pin Number, Inspector's ID Number, Date and Time, Operation Number, and Inspection Occurrence. Assemblies failing to meet a specified defect threshold are automatically identified, and the Inspector is informed by the system to set them aside for analysis and Corrective Action. CCAs not requiring Corrective Action are passed on to subsequent assembly or touchup operations per the standard routing.

Rework Operators also have access to the IWS screens, but in a view-only mode. By retrieving the DID and the database records, the Rework Operator can view the locations requiring rework, and those which have been defective more than once and require MRB action. After rework, Production Inspectors use the same system to approve previously marked defect locations, again in a point-and-click fashion.

The database of inspection records also furnishes the raw data for a variety of process graphics which provide CCA Yield, Percent Defective, Defect Pareto, and Process Cycle Time measures for the assemblies and processes of interest. Production Management, Manufacturing Engineering, and Product Assurance use

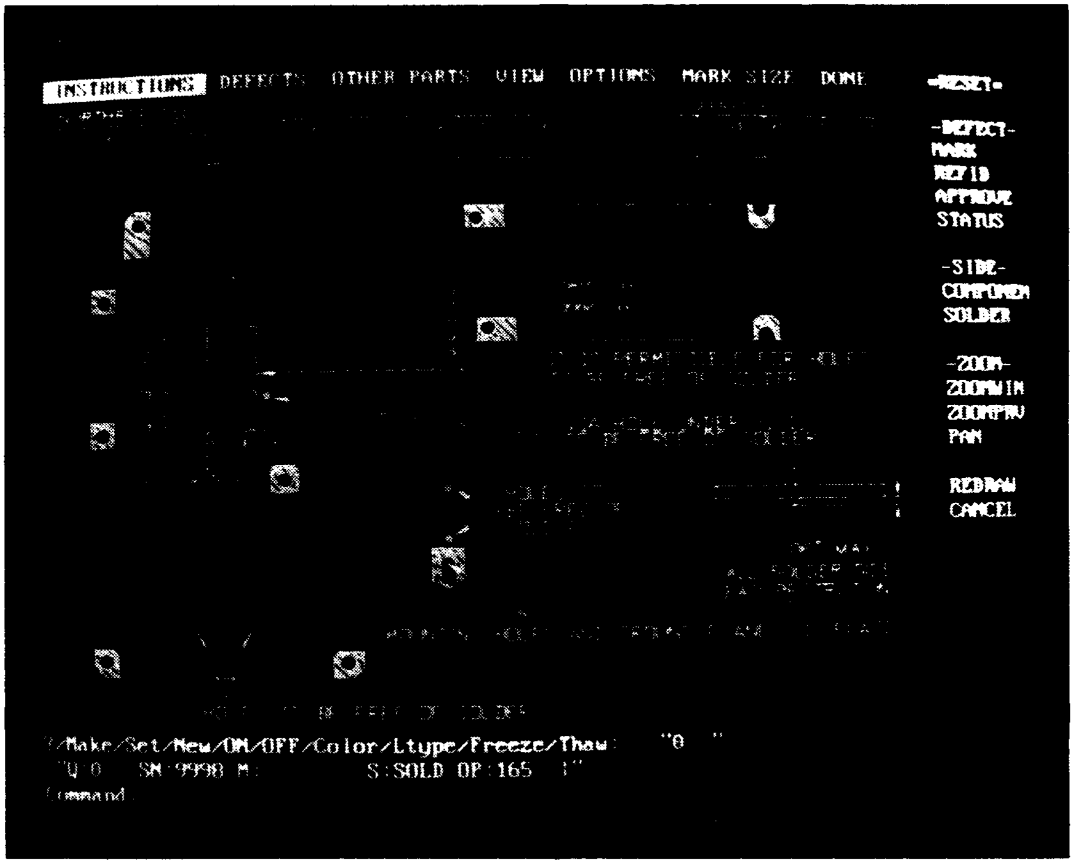

FIGURE 2. Example Defect Identification Drawing (DID)

these graphics to track production quality and isolate problem areas.

In addition, process parameter settings ("Recipes"), Statistical Process Control (SPC) Control Charts, and online Corrective Action Tracking are maintained in the same database.

BACKGROUND

A paper-based system for inspection data collection was in place at Northrop prior to the development of the IWS in 1989-'90. Graphic drawing files, created by Industrial Engineering and using AutoCAD (Autodesk, Inc., Sausalito, CA), as part

of an Automated Work Instructions (AWI) system, depicted the solder and component sides of each unique CCA. A paper copy of the graphic accompanied each assembly through its standard process routing. Production Inspection (PI), using a red pen, marked defect locations and defect codes on the sheet as they were discovered, and transcribed the data onto a daily in-process inspection data log, for keypunching into a database maintained by Product Assurance (PA). Deficiencies of that system, from a data analysis perspective, were numerous: handwriting on the graphic data sheets routinely became illegible; locations of defects were difficult to pinpoint exactly; errors in tabulating defect quantities were common; raw data did not reach PA, nor was it entered into PA's database, in a timely fashion (and consequently was useless for process control); PA could not track defects by part number or pin location. The existing inspection data was of marginal use to Manufacturing Engineering for process improvement, since detailed information was not compiled centrally, but travelled with the product. The IWS was conceived primarily to address these data deficiencies.

REQUIREMENTS

The IWS system was developed to provide efficiency and accuracy improvements in Production Inspection, while complying with the Naval Weapons Specification WS-6536E (Reference 1). It has recently been updated to also meet the requirements of the Military Standard MIL-STD-2000 (Reference 2). The system is expected to easily conform with any future or superseding specifications.

A variety of measurement and data collection systems are available as commercial products, ranging from simple data loggers to fully automated inspection systems. However, none of these met ESD-Rolling Meadows' needs, which were driven by factors such as the diversity and low volumes of unique assemblies, the complexities of military specifications and their workmanship acceptance criteria for soldered assemblies, the rigorous data collection requirements imposed by DOD customers, and the need for compatibility with existing data systems at ESD-Rolling Meadows. In Northrop's environment, where human inspectors using magnification aids continue to provide the most reliable interpretations of the specification standards, the IWS system would focus on efficient data acquisition and use.

The IWS system had to utilize existing assembly data (Bill of Materials, Work Instructions, etc.), and be compatible with other information systems, to the greatest extent possible. An Oracle Corporation (Belmont, CA) Relational Database Management System (RDBMS), the Division standard, was required. To minimize

variable costs, DIDs had to be produced by way of modifications to the existing AWI Visual Aids, in AutoCAD format. Process Operation Numbers and Inspection Steps, part of the Standard Routings, required validation by the IWS system courtesy of a daily download from the AWI database. On the factory floor, the use of existing 80386-based DOS computers was a given. Users had to have the capability to toggle between the IWS application and existing mainframe sessions (such as labor reporting, material requisition, and display of AWI, via terminal emulation) with the touch of a key. The user interface had to be simple and straightforward, to accommodate users without appreciable computer skills.

Finally, to permit the conversion of inspection results from raw data to valuable information, a graphical data analysis tool, using the querying capabilities of the relational database, was required. The Process Graphics Module of the application would present parameter selection forms to an online user, allowing him to automatically retrieve the desired results from the database without a working knowledge of the structured query language (SQL), tables, or data fields used. The data returned from these queries was to be converted to graphical output -- Line Graphs and Pareto Charts -- for high visual impact.

TECHNICAL APPROACH

Highest priority was given to ease-of-use. A design goal was to permit all required functions to be executed using a mouse, or through data entry forms. No command line activity would be permitted. Any forms would be implemented in Oracle Tools for the PC, which executes forms locally, and provides network access to the central database. TCP/IP (Transmission Control Protocol/ Internet Protocol), over an Ethernet network, was chosen as the networking protocol, for its performance, ease of installation and maintenance, and status as a common standard.

Setup

For inspection, an Oracle form was designed to accept user input of setup parameters such as Circuit Card Assembly Number, Serial Number, and Operation Number (Figure 3). This information is sufficient to retrieve the DID from a directory on the server, along with any previous defect records from the database, at which point AutoCAD is executed and the mouse enabled. The input form data also is assigned to variables which are to be used in the creation of database records

at the end of the session.

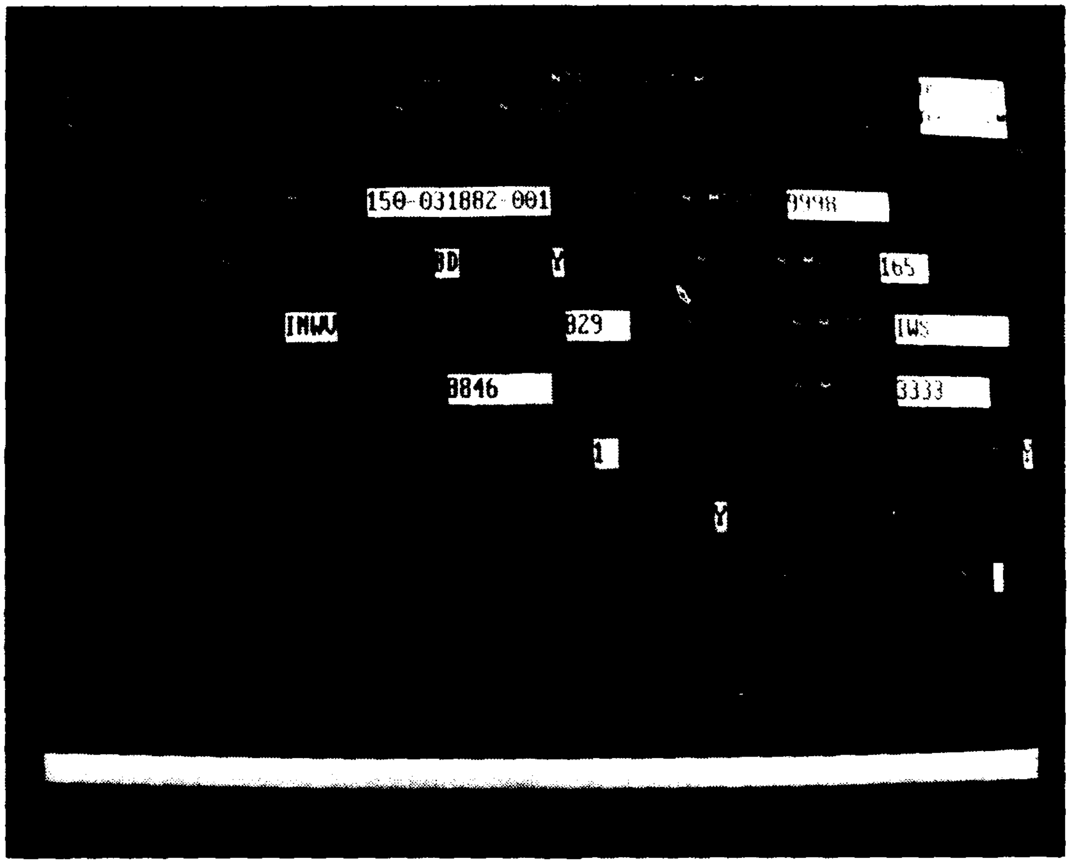

FIGURE 3. IWS Header Form

Customized menus were developed to be invoked within AutoCAD, for executing particular functions (visible along the top and right-hand sides of Figure 2). Some functions are part of the standard library of AutoCAD commands (Zoom, for example), while others are custom AutoLISP routines (e.g., drawing defect marks on the DID). The menus are compiled at run time.

AutoLISP is the AutoCAD programming language, a functional object-oriented implementation of LISP. In addition to the custom features, all internal linking of the IWS programs and the data extraction to the database are accomplished in AutoLISP. AutoLISP controls the use of global AutoCAD variables and DOS

environment variables, particularly for memory control, as the IWS works.

Graphics

The IWS executes AutoCAD on each user's station to display DIDs. DIDs are maintained as current by making them part of the AWI package, downloaded nightly to the database server. Since this download corresponds with the update schedule for AWI, DIDs always match the work instructions on the factory floor.

DIDs were developed from AWI Visual Aids. Existing V.A.s were modified in two ways to become DIDs.

First, layering was added to the AutoCAD V.A.s, with each layer containing the components populated at a particular operation. Use of a different color for each layer emphasizes the differences in CCA objects, e.g. blue for plated through holes, green for surface mounted components, purple for through hole components, etc. By turning on the AutoCAD display for appropriate layers in sequence, then, depending on which operations had been completed, the IWS shows exactly how the CCA should appear to the Inspector at each particular inspection operation. Header, Printed Wiring Board, and Through Hole layers are always turned on. Other layers are named in the manner of C01 and S01, C012 and S012, C0123 and S0123, etc., in the reverse order of CCA assembly operations. The use of a wild card determines which layers are turned on at any selected operation. The character '*' matches zero or more occurrences of any character, so may be used to turn on multiple layers at once. For example, based on user input of a particular operation number, layers C012* and S012*, when turned on, display all layers except C0, S0, C01 and S01, which are used to show the components added at future operations. The C and S prefixes, for Component and Solder sides of the assembly, are used for x-y positioning within the DID graphic file, allowing the user to display one side or the other with a click of the mouse.

The second V.A. modification was to define blocks and assign attribute names to every individual feature on the drawings, to indicate the reference designators and pin numbers of components. For example, a part outline might be named R1 for the resistor R1, and the through-holes on either end named R1.1 and R1.2. When selected with the click of the mouse, an object's attribute name is used by the program to store the identity of the rejected component and pin number.

In AutoCAD, "blocks" are the entities which are made to correspond to individual

features on the drawing. In the CCA drawing application, each block is given a layer name (as described above), attribute name (such as 'R1.1'), and a tag ('PINID' or 'REFID', to indicate whether or not the block value contains a pin number). The program handles the two tag types differently. When a PINID, or solder joint, feature is selected, the string is separated and assignments made to two variables (part_ref = 'R1' and pin_ref = 'R1.1'), whereas when a component body, or a feature without pin numbering, is selected, the part_ref variable is assigned (part_ref = 'R1') while the pin_ref variable is null.

Care was taken to ensure that the Design Engineering CAD systems could implement the same layering and object attributes, so that future design drawings could automatically be used as DIDs with little or no modification.

Inspection and Display Control Features

Whether custom or standard, all required functions are executable via the mouse. Each function loops in execution mode until canceled by another program selection. Descriptions of some of the key features follow.

* Mark Mode - In Mark Mode, a pick box is manipulated by the Inspector to select an object, after which the pulldown Defect Code Menu appears (Figure 4). The user selects the appropriate defect code, chooses the orientation of the mark, and clicks the mouse. The Mark is a square box of selectable size, with an arrow pointing to the defective location. Each Mark displays the defect code, the type of defect ('A' for Assembly, 'S' for Solder, or 'P' for Process Indicator), and the number of times the location has been inspected and found defective (Figure 5).

* Text Inspection Instructions - The full Work Instruction text for the current operation is imported to a series of AutoCAD pulldown windows, available for immediate viewing. This eliminates the need for the inspector to refer to the AWI system during the course of an inspection. A routine controls pagination of the instruction windows, and options allow the user to refer to the instructions in virtually any order.

* Defect Code Menu - Standard Defect Codes, used throughout ESD-Rolling Meadows Manufacturing Operations, are categorized by defect types and listed in a series of pulldown menus. The same menus act both as reference, and for defect code selection when marking defect locations.

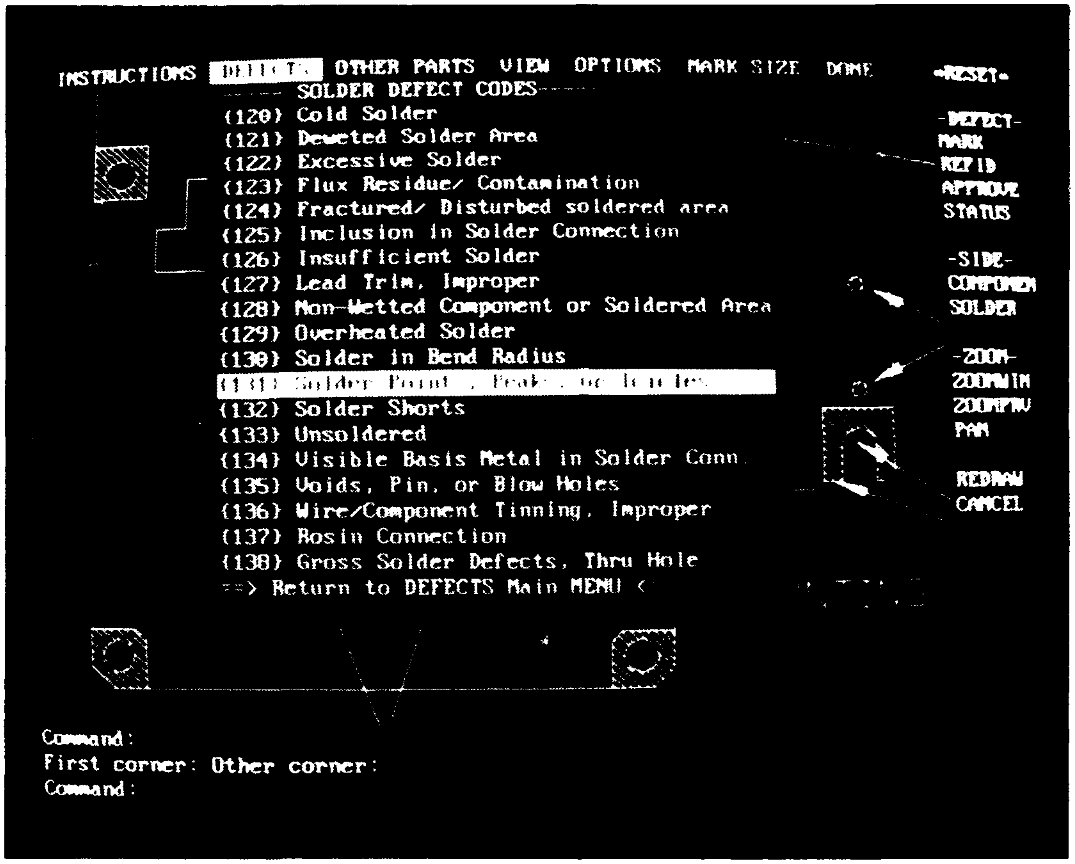

FIGURE 4. Defect Code Menu

* Views (e.g. Quadrants), Side (Component or Solder), Zoom Window, Zoom Previous, Pan - AutoCAD features are assimilated into menu selections to allow the user to completely control the display of the graphic.

* Mark Size to control the appearance of the Marks -Depending on the complexity of the CCA, the user may wish to increase or decrease the size of the defect marks in order to enhance visibility.

* Select and Erase to Edit Defect Marks - The Inspector uses these functions to remove unwanted marks (for the current operation only, to maintain security of the data).

* Refid - A feature was included to permit the user to assign a defect to a region

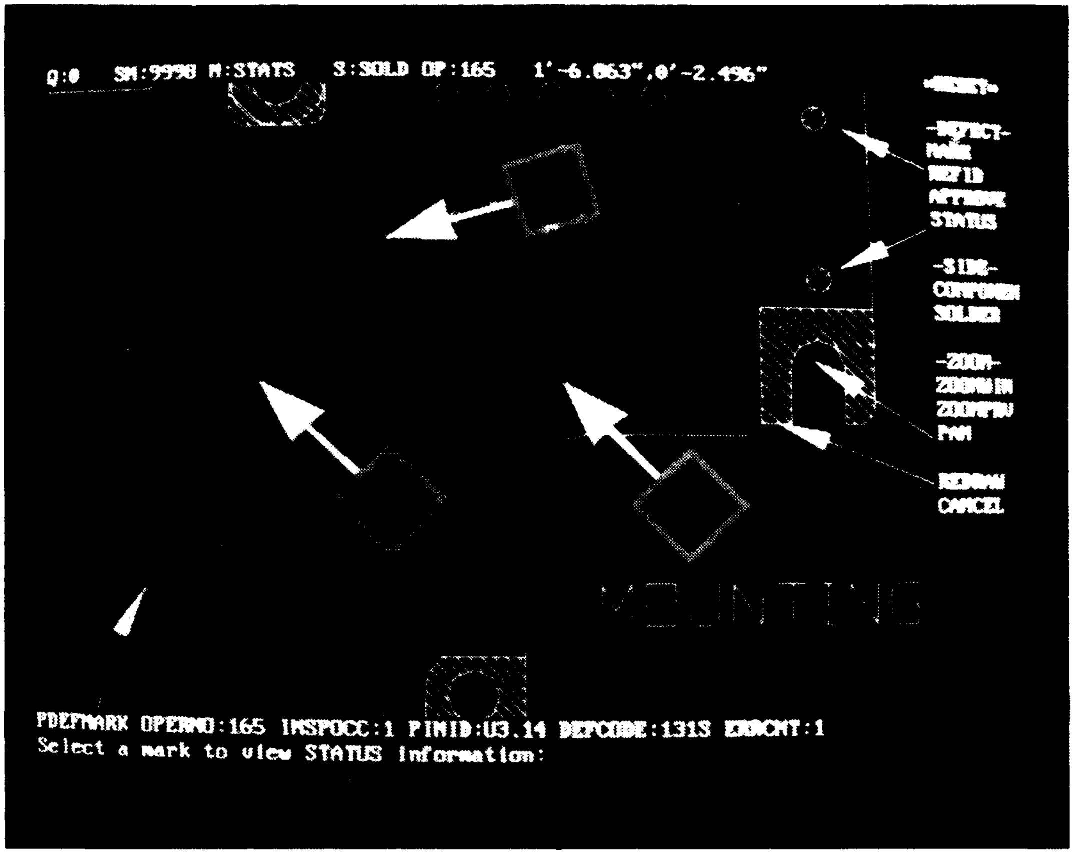

FIGURE 5. Example Defect Marks

of the CCA, rather than to a predefined object. This function stores the x-y location of the defect mark, but no values for the part_ref or pin_ref variables. An example of the correct use of this feature would be to indicate a scratch on the Printed Wiring Board surface.

* Approve - When CCAs are submitted for re-inspection, the Inspector clicks on previously drawn marks. The IWS redraws each mark with a circle around it, and executes database updates, to denote successful rework.

* Previous Mark - While in Mark Mode, if the Inspector clicks on an existing mark, rather than on a drawing object, the count index is incremented for that defect. This is used to indicate the number of times a defect has been detected at that particular location. The Inspector may or may not update the defect code, as

required.

* Status - This option allows the user to view key parameters of defect marks, at the bottom of the screen, without having to zoom in. Figure 5 shows the Status Mode display.

* Done - "Exit and Save" or "Quit and Don't Save" to finish the current inspection.

When inspection of a given assembly is completed, a routine extracts inspection data from AutoCAD and populates the database, terminates AutoCAD, and resumes running Oracle forms. A tabular display sums the number of assembly and solder defects, and indicates to the Inspector whether or not Corrective Action is required, per predetermined criteria.

Graphical Analysis Tools

The primary graphical tools developed for analysis of inspection results are Line Graphs and Pareto Charts. The Line Graphs present up to three separate data lines, with the x-axis being time units and the y-axis being Yield, Percent Defective, Volume, or Cycle Time. The distinct data lines may segregate solder from assembly defects, first-pass from second-pass defects, or actual data from an eight-point moving average, to name a few examples. The legend at the bottom identifies each line, and the heading at the top displays the parameters selected. Figure 6 shows an example Line Graph of Percent Defective, for first-pass Solder Defects, and the corresponding eight-point moving average. All of the attributes are selectable by the user in real time, through use of Oracle forms.

The Pareto Charts implement up to two sorts, in descending order, to permit the user to identify "high-hitters", in order to prioritize problems. A Pareto is a block diagram, with the primary sort variable of interest along the x-axis and, in this application, Number of Defects or Percent Defective being the dependent variable. A secondary sort is implemented by using different colors to "stack" the bars, with the legend at the bottom identifying the colors. Figure 7 shows a typical Stacked Pareto Chart. A variety of selections are available on the data input forms for the primary and secondary sort variables, and the data pool to be sorted can be limited by parametric selections such as the operation type, date range, assembly number, etc., most of which are optional.

The graph to be constructed is selected via an Oracle form, and the user builds the

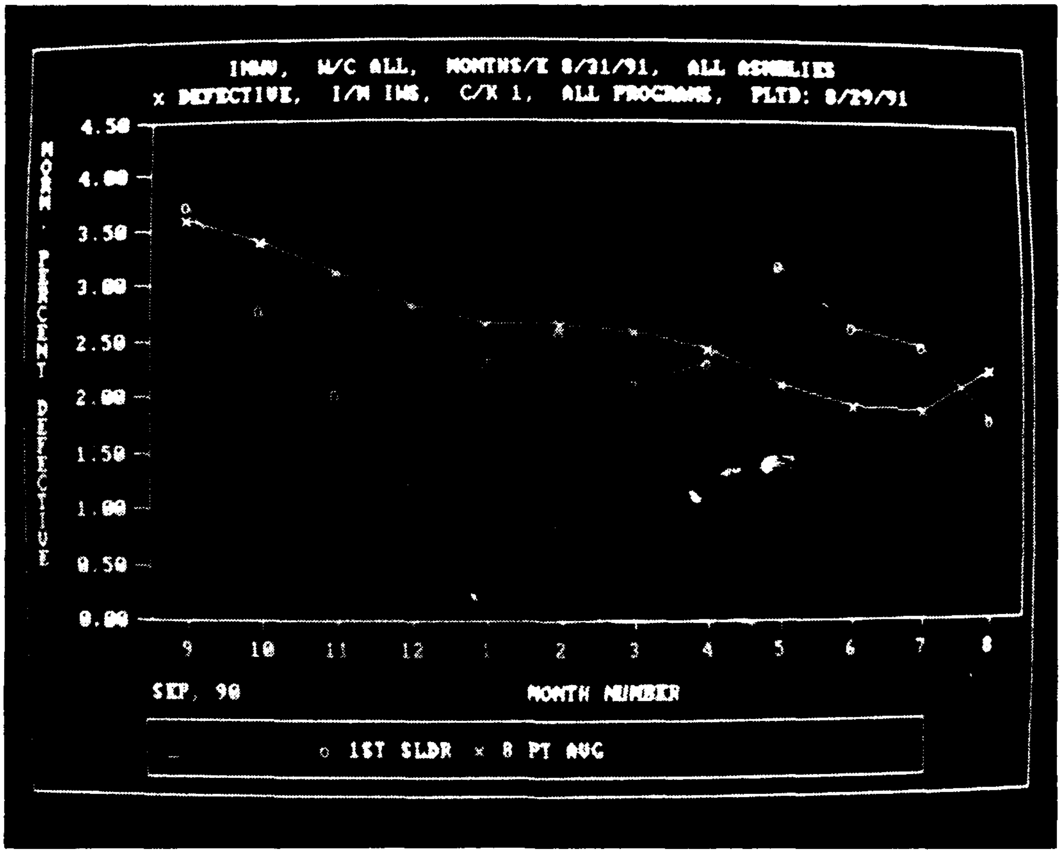

FIGURE 6. Example Line Graph of Percent Defective and Eight-Point Moving Average

appropriate database queries by filling in the form(s) with the parameters of interest. Figure 8 shows the Pareto Selection Form, as it appears when first executed (default values filled in).

C-Language Programs, using Oracle's Pro*C as the high-level language to define and manipulate RDBMS data, translate the data inputs from the forms into a set of queries, which are then transmitted over the network to the database server for execution. Query results are returned to the local station, where a routine converts the data into a flat file. A custom Plot Utility, executing on the user's station, accepts the flat file of data points, header strings, legend strings, and detail data (for display in selectable text-formatted windows), and converts these inputs to display the chart on the monitor.

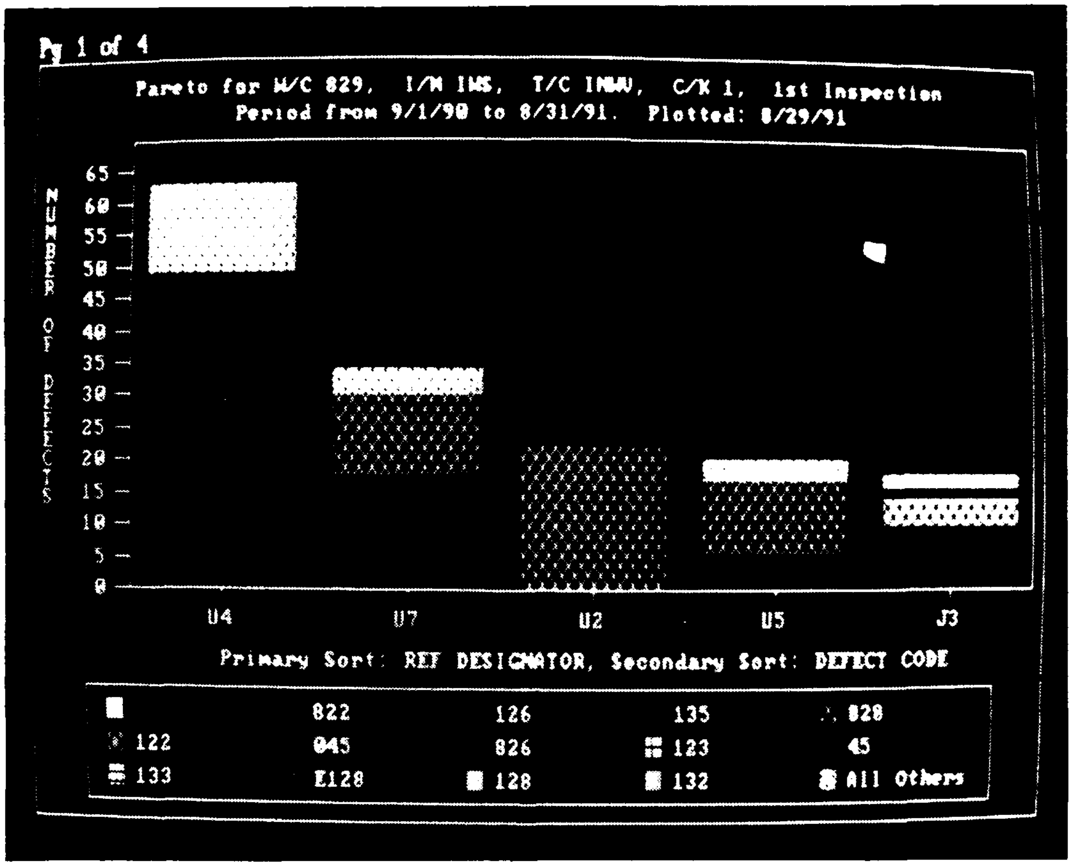

FIGURE 7. Example Stacked Pareto Chart

IMPLEMENTATION DETAILS

The IWS station is an 80386 with 4 MegaBytes (MB) of RAM, equipped with an 80387 Math Coprocessor, a minimum of 40 MB Hard Disk, TCP/IP Network Interface Card, SNA Interface Card to communicate with the Mainframe, VGA Monitor, and three-button Mouse. Oracle Forms running on the local processor provide the initial user interface, and Pro*C and Microsoft (Redmond, WA) C are the C Programming interfaces to Oracle. AutoCAD Release 10 is used for creating and displaying the online graphics. DesqView 386 with QEMM Memory Management software (both from Quarterdeck Office Systems, Santa Monica, CA)

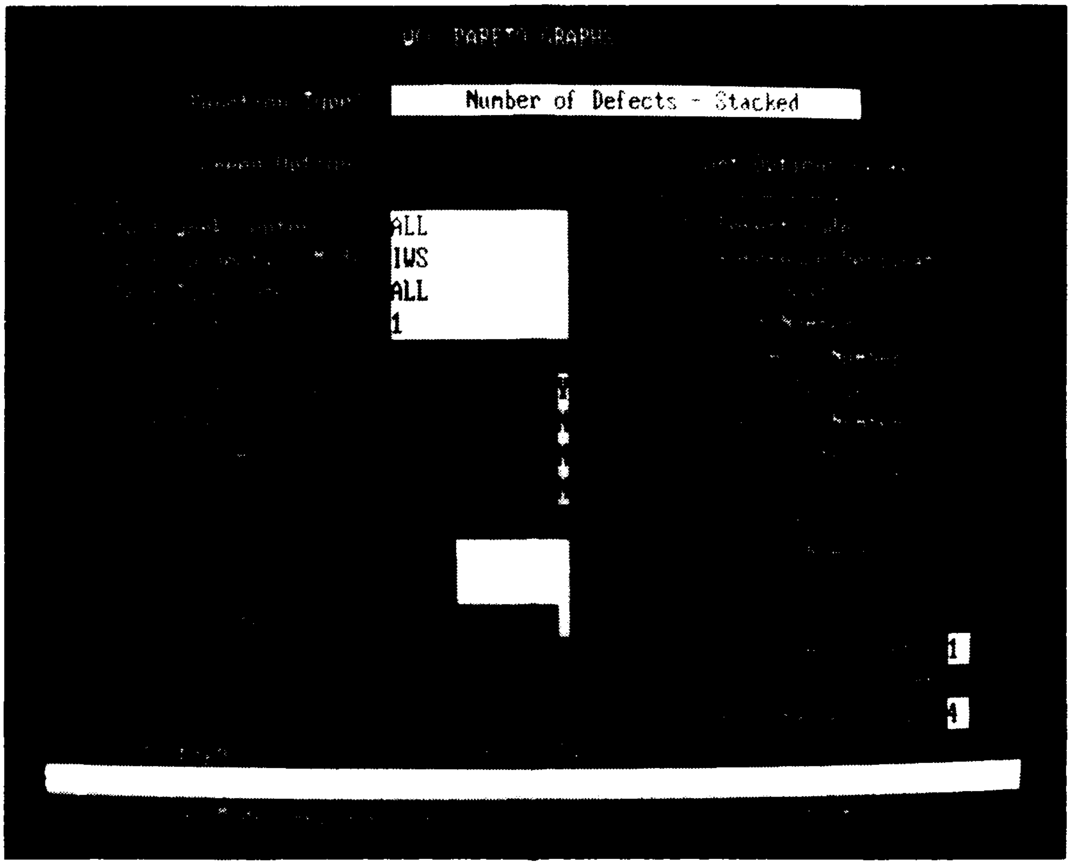

FIGURE 8. Pareto Chart Selection Form

are used to control the session and allow the user to toggle to SNA or PC applications via a "hot key".

Some stations are implemented without the IWS capability, but with custom Oracle forms required for non-graphical data retrieval and other functions. These stations may be 80286, and do not require the SNA Interface.

The database server is a Hewlett-Packard (Mountain View, CA) Series 9000 UNIX minicomputer running Oracle RDBMS software. Access to Oracle is granted transparently to the user, via the interface to Oracle Forms and SQL*TCP, running on the local station.

A print server, consisting of an 80286 with Coprocessor, 4 MB RAM, 40 MB Hard

Disk, DesqView and QRAM Memory Management Software for the 286, and a laser graphics printer, is used for producing hard copy of graphic charts.

TRAINING AND USER ACCEPTANCE

IWS training and documentation was provided to users through a combination of hands-on sessions, a detailed User's Manual, and a compact User's Reference Card. One hour training sessions with two users at a time proved to effectively get Inspectors started. Within a few hours, one Inspector was confident enough with the system that she was presenting demonstrations to upper management.

Initially, performance issues limited PI's efficiency with the IWS. The computation time to validate the setup data, retrieve a DID, execute AutoCAD, compile and execute the custom menus, and retrieve any existing defect data from the database often approached two minutes. Data transfer, from AutoCAD to the host database, at the conclusion of each inspection was of comparable duration. Though Inspectors could perform other tasks during these times, minimal overall cycle time improvements were experienced at first. Subsequently, however, indexes were added to the database, and additional memory was installed on the database server to improve performance. Today, PI requires fewer Inspectors, and Work-In-Process at Inspection has been virtually eliminated.

Rework Operators, and Engineers from Product Assurance and Manufacturing Engineering have also learned and accepted the IWS system, often with no formal training. Confident users have become trainers for others.

The Process Graphics functions were installed for Engineering users once inspection data was being collected. Weekly Reports produced from the database were widely distributed to demonstrate some of the analysis capabilities to management. As with the IWS, a User's Manual and word-of-mouth have served to disseminate information about the system.

POTENTIAL FOR ENHANCEMENT AND EXPANSION

Currently, use of the system is directed towards inspection of CCAs exclusively. However, any piecepart, subassembly, or assembly that can be graphically depicted in AutoCAD's drawing format could be inspected. Defect codes appropriate to the

application would need to be listed in a database table and AutoCAD menu. AutoCAD graphics, depicting the parts or assemblies to be inspected, would need to incorporate a standard set of layers, and unique objects would have to be defined and named in order to save specific location and/or component information to the database.

Additional data items or unique functions could be implemented in a straightforward manner. For example, at ESD-Rolling Meadows, use of the IWS for collection of SPC data and automatic control charting is currently being studied. Such functions need not be limited to defect data, nor must they be constrained to attribute data in general. Any data collection problem which would benefit from online graphical depiction, mouse-driven input, and the advantages of relational database storage and retrieval, could be addressed by a modified version of this system.

ACKNOWLEDGEMENTS

The engineers primarily responsible for the IWS were Kurt Sterbenz and Roger Rueff. Database design was done by Kitty Karmell, Karen Chrusciel and Mike Brown. The Process Graphics Module for data analysis was the work of Ken Masonick, Steve Price and Pablo Diaz. Others that had a hand in the project include Mark Lakomski, Rudy Benavente, Steve Bradford, Al Washington, and Rich Hennek. Finally, the Production Inspection group, headed by Lillian Bolden, deserves credit for its rapid acceptance of the IWS, and for its important feedback leading to system improvements.

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1. Naval Air Systems Command, Department of the Navy Process Specification, *Procedures and Requirements for Preparation and Soldering of Electrical Connections*, June 10, 1985.

2. Department of Defense Military Standard, MIL-STD-2000, *Standard Requirements for Soldered Electrical and Electronic Assemblies*, January 16, 1989.

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